Parameters of Indoor Air Quality (IAQ) in Wooden Houses

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Indoor environment quality in wooden family houses was compared to bricked houses or concrete slab apartments. Based on measurements, the influence of selected systems of forced ventilation without heat recovery and with efficient heat recovery were compared in selected houses in consideration of monitored parameters of CO_2 and relative humidity in the course of 24 hours. Auxiliary parameters such as temperature and absolute pressure were also measured. The CO_2 and relative humidity parameters had demonstrable effects in all the houses. The differences of CO_2 values while using recuperation or not in wooden houses reached 21.2%, 44.7%, and 31.6%. The relative humidity value differences reached 6.6%, 2.8%, and 2.9%. More significant differences in values were reached in the course of measuring in a brick building - 73.1% CO_2 and 39.4% of relative humidity. In the concrete slab apartment, the value differences reached 46.1% CO_2 and 1.8% at relative humidity. The permitted limit of 1,500 ppm of CO_2 was exceeded in all the objects without active heat recovery. In the case of efficient heat recovery, the values oscillated around the recommended value of 1,000 ppm of CO_2.

Keywords: Indoor air quality; Wooden houses; Ventilation; Heat recovery; CO_2; Temperature; Relative humidity; Absolute pressure

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INTRODUCTION

The human population spends up to 90% of time indoors. The time of staying indoors differs depending on age, occupation, and other circumstances. In any case, a man spends approximately one third of a day by sleeping or by having rest. The indoor environment quality in residential buildings is set by the building characteristics and its technical equipment as well as by human activities to a significant level.

In consideration of the fact that people spend so much time indoors, it is necessary to adjust the premises accordingly. It is very important to meet specified limit values of main parameters determining the indoor environment. Meeting the values will provide for the environment to be suitable for work or rest – *i.e.* for long-term stay. Research indicate that as much as 50% of all the diseases depend on quality of indoor environment where people spend their time (Landrigan *et al.* 2018).

The content of pollutants is the most frequently detected value in buildings; the pollutants are emitted to the environment from various sources, *e.g.* construction materials, furniture, plastic utensils, combustion processes, *etc.* (Svoboda *et al.* 2015; Kauneliene *et al*. 2016). Pollutants contain some quantities of aldehydes, alcohols, esters and phthalate esters, fragrances and other chemical substances (Gale *et al*. 2009). Suitable ventilation or air-conditioning are the factors providing sufficient oxygen supply as well as elimination of the pollutants (Weschler 2009), which is frequently neglected because of heat savings (Øie *et al*. 1998). Besides chemical substances, the indoor environment is also affected by physical parameters of air, such as temperature, pressure or humidity, as well as by humans themselves, expiring carbon dioxide (CO_2) to the air. Just CO_2 is responsible to some level for symptoms belonging to the sick building syndrome (SBS), which in connection with low oxygen contents and unsuitable humidity causes many health problems (Apte *et al*. 2000; Dimitroulopoulou 2012). High contents of CO_2, as well as the SBS itself are caused by poor ventilation, heating, or air-conditioning of buildings (Fisk *et al*. 2009). According to earlier research of Seppänen *et al*. (1999), CO_2 directly affects some SBS symptoms, such as headache, fatigue, eye and nasal symptoms, respiratory symptoms (throat and lower respiratory system symptoms as well as difficult breathing). The connection of CO_2 and SBS further deepens in buildings with controlled ventilation. Unfortunately, the CO_2 limits for residential houses are not fixed in national standards in most of the European countries—only in Government instructions or EU directives. Globally, the recommended CO_2 limit of 1,000 ppm has been established and been applied for decades. The value of 1,000 ppm corresponds with CO_2 concentration of 1,800 mg/m^3. This value is set based on CO_2 quantity generated by a man indoors as well as CO_2 quantity in air supplied from the outside during ventilation. The necessary aeration rate per person is 7.5 l/s, and the supposed CO_2 production rate by a man is 0.005 l/s, which is in total 1,200 mg/m^3. The volume of CO_2 in air supplied from the outside is 600 mg/m^3, which in sum with the previous value makes 1800 mg/m^3 (ASTM D6245-12 2012; ANSI/ASHRAE 2016). Maximal recommended value in interiors of residential houses is set to 1,500 ppm. The value of 5000 ppm is stated to be the limit value – its exceeding means health risks and persons should not stay long in such premises (ASTM D6245-12 2012; ANSI/ASHRAE 2016). The contents of CO_2 and its influence on human health is a long-time discussed topic, even though there are not any clear results. Some research confirm the decrease of decision-making skills and performance just at the CO_2 concentration level of 1,000 ppm (Satish *et al*. 2012; Maddalena *et al*. 2015; Allen *et al*. 2016), but other research deny this, stating that it is the combination of the CO_2 influence and the interaction with other pollutants (Zhang *et al*. 2017).

Perfectly sealed new buildings as well as unsuitably performed revitalizations of old buildings negatively affect – from the sufficient ventilation point of view – the home environment (Korsgaard 1983; Pan 2010; Panayiotou *et al*. 2010; Vili *et al*. 2013; Langer *et al*. 2015). New types of windows with multi-level sealing and several glass panes prevent natural air exchange by infiltration that provided air exchange before. This problem can be partially solved by using windows with micro-ventilation, but unfortunately it is at the price of acoustic dampening reduction and heat losses. Users limit such ventilation to a minimal level due to fears of significant heat losses during ventilation through open windows or micro-ventilation. These problems can be currently solved by realization of controlled ventilation systems with heat recovery. Controlled ventilation with recuperation represents a continuous exchange of used air from the interior by fresh, clean air from the exterior. The air drawn inside obtains a prevailing part of heat from the air drawn outside, thus being optimised thermally; moreover, dust, pollen, and allergens are removed due to the used filtration. Sufficient natural or forced ventilation must be ensured for residential rooms, and such rooms must be sufficiently heated, with the possibility of regulation of internal temperature. Regarding ventilation of residential rooms, the minimum amount of exchanged external air of 15 m^3.h^{-1} per person (residential rooms) or the intensity of ventilation of 0.5 h^{-1} must be ensured when people are present. The systems may include installation of sensors measuring the CO_2 or humidity level and automatically react to the current quality of the indoor environment in residential premises. They can automatically solve the situation when the CO_2 or humidity level is above limit, and so it disturbs the indoor environment quality. Research comparing low-energy or passive buildings and standard buildings are performed less frequently. Most of the research studies are performed in Sweden, Finland, Denmark (Langer *et al*. 2015) or France (Derbez *et al*. 2014), while multifamily residential buildings in Central and Eastern Europe have been rarely investigated (Földváry *et al*. 2017).

This research was aimed at the indoor air quality (IAQ) parameters in five buildings, *i.e.* three wooden houses, one brick house, and one concrete slab apartment. The four parameters were monitored during 24-hour measurement. Carbon dioxide and relative humidity of air were the main factors, whereas the temperature and absolute air pressure were secondary factors.

EXPERIMENTAL

Locations

Measurements were performed in five different locations of the Central Bohemian Region and in the territory of Prague, the capital (Table 1). The conditions of measurement were completely identical, as the measurements were performed in the same time period in summer, without any weather changes such as heavy rainfalls or rain showers.

Table 1. Description of Investigated Buildings at Selected Locations

Building location	Building type	Description
Starý Vestec	wooden house	Low-energy wooden house made of type wall panels K-Kontrol (CZECH PAN s.r.o., Varnsdorf, Czech Republic). The measured room (parents' bedroom) is on the first floor of the building, east-orientated. There is installed the Lifebreath CAF-D-L4a36-ECM recovery unit (Airia Brands Inc., London, Canada).
Vinoř	wooden house	Panel wooden house with diffusion – open structure made in passive standard. The measured room (parents' bedroom) is on the first floor of the building, south and east-orientated. There is installed the Ultima iERV recovery unit (Jablotron Living Technology s.r.o., Holešov, Czech Republic) with enthalpic exchanger in the building.
Květnice	wooden house	Low-energy wooden house made of construction panels by HLC. The measured room (parents' bedroom) is on the first floor of the building, south and east-orientated. There is installed the ILTO 440 Premium recovery unit (Nativa spol. s r.o., Mikulov, Czech Republic).
Prague-Uhříněves	brick house	Low-energy new brick house made of Porotherm brick, the façade is insulated with polystyrene. The controlled ventilation system with heat recovery is based on heat recovery unit Ventbox 300 (ThermWet s.r.o., Prague–Uhříněves, Czech Republic).
Prague-Pankrác	concrete panel apartment	The house is built of concrete panels using the T08B system, with insulated façade. The measured room (parents' bedroom) is on the first floor of the building. Measuring was performed using the micro ventilation of plastic windows.

In concrete terms, there were included the wooden houses in Starý Vestec, Vinoř and Květnice, then a brick house in Prague – Uhříněves, and a concrete slab apartment in Prague - Pankrác. The concrete slab apartment was located in a panel block of flats which had been constructed using the T08B system representing one of the most common construction systems, which consisted of vertical reinforced concrete panels placed next to each other – constructed in Czechoslovakia in the time period of 1962 to 1980. The respective structures were chosen considering the commonly used construction systems in the Czech Republic. Three types of wooden constructions, which are the most used in the Czech Republic, have been chosen. For this reason, the following five types were mentioned as the typical representation of buildings for housing.

Measurement

Measurements of CO_2, relative humidity, temperature, and absolute pressure were performed in selected rooms of the buildings with an identical floor size of 25 m^2, using the device Testo 435 - 2 (Testo SE & Co. KGaA, Lenzkirch, Germany) with an external IAQ probe. Measurements were performed for the purpose of assessing air quality in the room in the course of 24 h with switched-on or switched-off controlled ventilation system with heat recovery. The results were assessed using the software supplied by the manufacturer of Testo Comfort – Software X35.

In all of the surveyed houses, the device with the probe was placed in the bedroom inhabited by two adults, with comparable air volume. The probe was placed in the height of 700 to 900 mm above the floor and with a minimum distance of 1.5 m from persons. Measurements were performed with the door closed so as not to be affected by air from other residential premises. Measuring was always performed for 24 h and values of CO_2, relative humidity, temperature, and absolute pressure were recorded every 10 min; 144 individual measured points were obtained from each 24-hour measuring cycle. The CO_2 value is the critical parameter for indoor environment quality.

Fig. 1. Testo 435 – 2 measuring instrument with IAQ probe

RESULTS AND DISCUSSION

Wooden house – Starý Vestec

Two measuring cycles were performed in this wooden house made of K-Kontrol panels and the results are stated in Table 2. The first measurements were performed without controlled ventilation and heat recovery (Fig. 2), while the second measurements were performed with controlled ventilation switched-on (Fig. 3).

Table 2. Measured values of parameters in Starý Vestec

		Carbon dioxide (ppm)		Absolute pressure (hPa)		Temperature (°C)		Relative humidity (%)	
Controlled Ventilation + Heat Recovery		no	yes	no	yes	no	yes	no	yes
Value	minimum	590	532	992	987	20.3	18.5	33.9	31.1
	maximum	1,035	870	997	995	24.1	24.5	44.3	37.6
	average	830	654	994	992	22.4	22.9	36.2	33.8

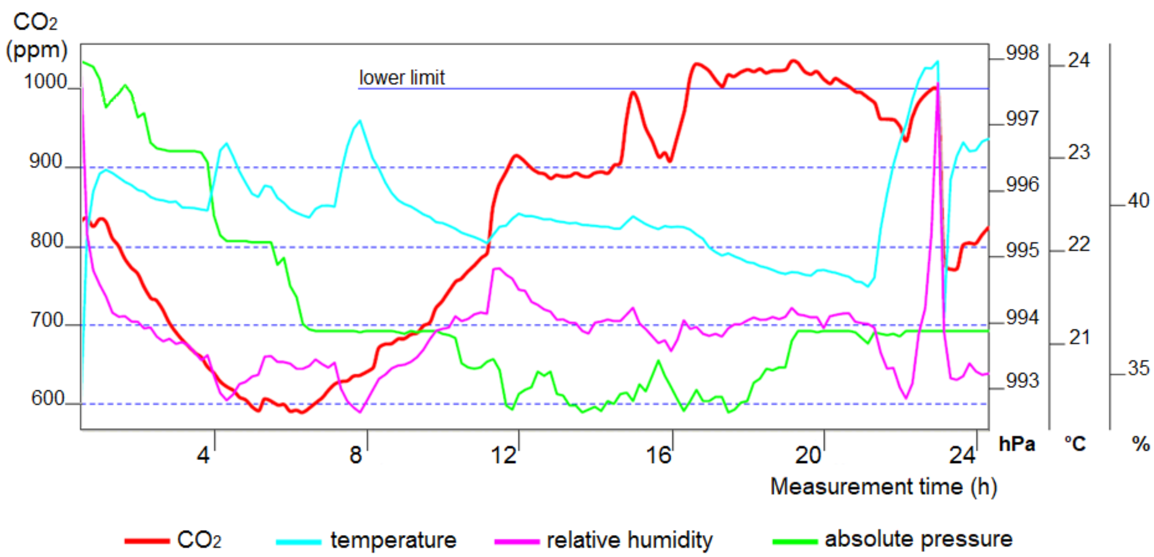

Fig. 2. The course of monitored air quality parameters without controlled ventilation and heat recovery in Starý Vestec

The CO_2 curve in Fig. 2 clearly indicates the start of use of the surveyed bedroom and the people going to sleep at about 8.00 p.m. For the entire sleeping time, the CO_2 values oscillated around the acceptable value of 1,000 ppm. A rapid decline in CO_2 and temperature values at 8.00 a.m. indicates bedroom ventilation through a window. The relative humidity increase just before ventilation was caused by use of the bathroom adjacent to the surveyed bedroom, with direct entry to it.

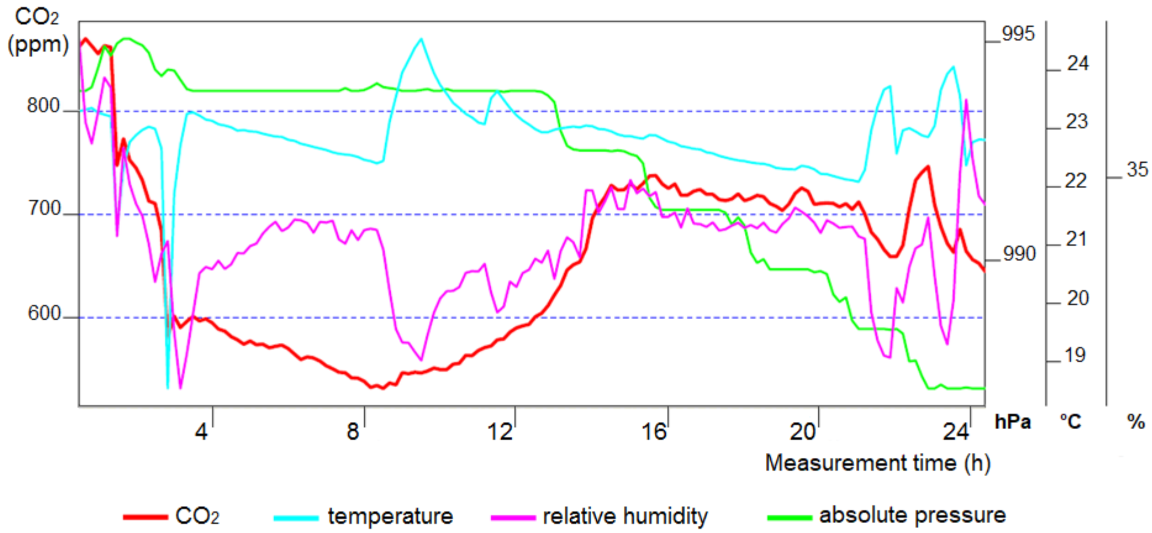

Fig. 3. The course of monitored air quality parameters with controlled ventilation and heat recovery in Starý Vestec

The monitored values measured in the course of controlled ventilation operation are shown in Fig. 3. The main determining parameter of indoor environment quality, CO_2, moved along acceptable limits. The only extreme was the temperature and relative humidity decrease after 12:00 p.m. caused by ventilation through the window.

In both cases, the CO_2 value remained below or at the recommended CO_2 limit value of 1,000 ppm, *i.e.* well below the limit value of 1,500 ppm. In both cases, relative humidity remained at the lower limit of recommended values.

Wooden House – Vinoř

Even in this wooden house of panels, two measuring cycles were performed, and the results are specified in Table 3. The first 24-h measurements were performed without controlled ventilation (Fig. 4), while the second measurements were performed with controlled ventilation switched-on (Fig. 5).

Table 3. Measured Values of Parameters at Vinoř

		Carbon dioxide (ppm)		Absolute pressure (hPa)		Temperature (°C)		Relative humidity (%)	
Controlled Ventilation + Heat Recovery		no	yes	no	yes	no	yes	no	yes
Value	minimum	883	708	972	984	19.6	20.2	27.1	33.1
	maximum	2,392	1,714	977	989	30.4	26.4	46.3	49.8
	average	1,817	1,004	975	987	24.1	23.7	38.9	40.0

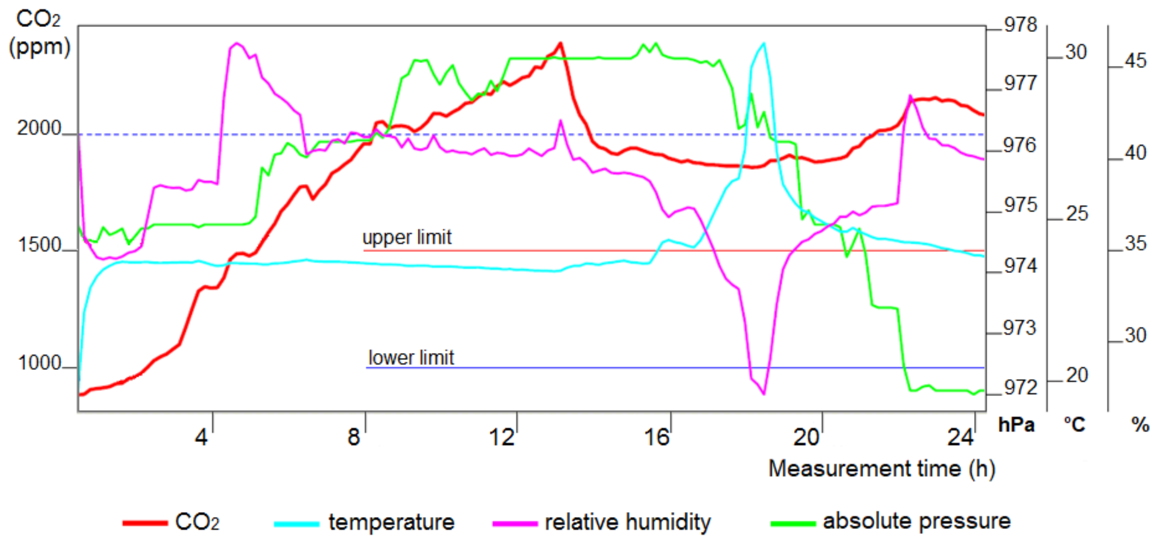

Fig. 4. The course of monitored air quality parameters without controlled ventilation and heat recovery in Vinoř

CO_2 values in Fig. 4 indicate that the surveyed bedroom was used approximately from 8.00 p.m. The maximal allowed limit of CO_2, which is 1,500 ppm, was exceeded at 10.00 p.m. and the CO_2 value increased to 2,392 ppm at 5:50 a.m. when the inhabitants woke up. An interesting indicator is the increase of temperature in the bedroom at about 11.00 a.m. due to heat gains from sunshine due to south-east orientation of glass surfaces and sunny weather. Humidity decrease can be observed against the temperature increase.

Figure 5 shows monitored values with switched-on controlled ventilation system. Based on the CO_2 curve it is possible to discover for the people to go to bed at 11.00 p.m. The CO_2 values were within acceptable values, except for the time period from 2.00 a.m. to 6.00 a.m., when they woke up. The values exceeded the upper limit of 1,500 ppm by a maximum of 214 ppm.

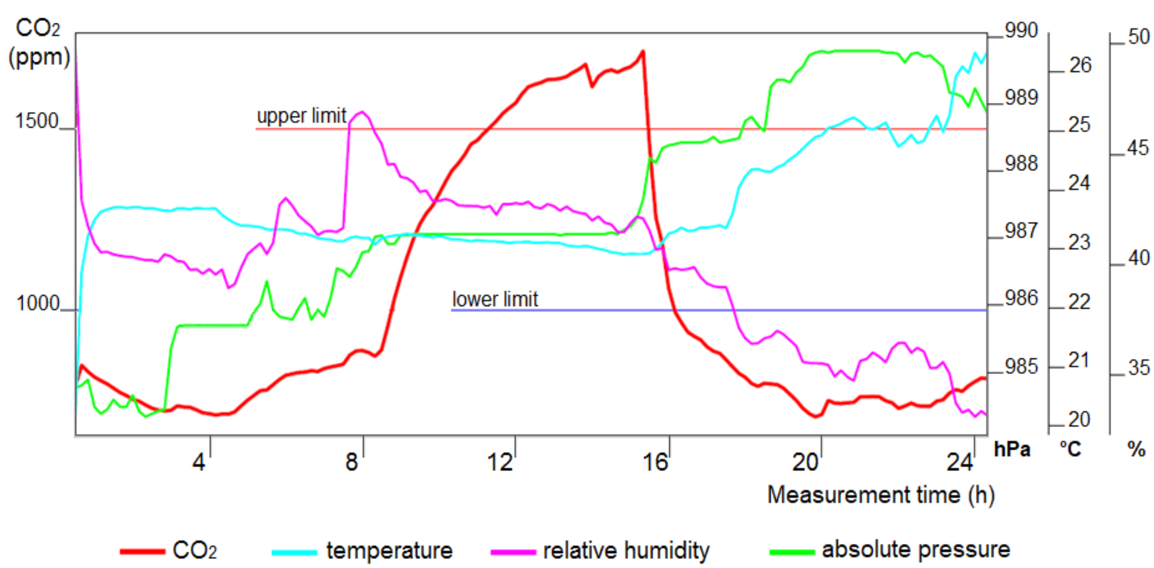

Fig. 5. The course of monitored air quality parameters with controlled ventilation and heat recovery in Vinoř

In the course of quiet period over the day when the room was not inhabited, the CO_2 value was 750 ppm, which is below the lower limit of 1,000 ppm. It is also possible to identify the decrease of relative humidity depending on temperature increase, due to installed hot-air heating of the house. Even while using the controlled ventilation, the maximal CO_2 value exceeded the maximal recommended value of 1,500 ppm at night in as much as 214 ppm.

A simple solution of the problem could be the installation of a CO_2 sensor in the measured room. In the case of exceeding the pre-set CO_2 limit, the sensor automatically reacts and it increases the power of the unit, allowing better ventilation. Without the controlled ventilation system in the building, the environment was over-dried. The lowest measured value of relative humidity was 27.1%. The problem was solved by the unit with an enthalpic exchanger that regulates the humidity in the building.

Wooden house – Květnice

The low-energy wooden house located in Květnice is made of construction panels of the company HLC. Table 4 states the results of measuring without controlled conditioning and with switched on conditioning.

Table 4. Measured Values of Parameters at Květnice

		Carbon dioxide (ppm)		Absolute pressure (hPa)		Temperature (°C)		Relative humidity (%)	
Controlled Ventilation + Heat Recovery		no	yes	no	yes	no	yes	no	yes
Value	minimum	524	561	983	983	20.2	21.7	31.6	38.8
	maximum	2,579	1,680	987	985	25.0	22.9	54.5	50.1
	average	1,560	1,067	985	985	22.8	22.4	45.6	44.3

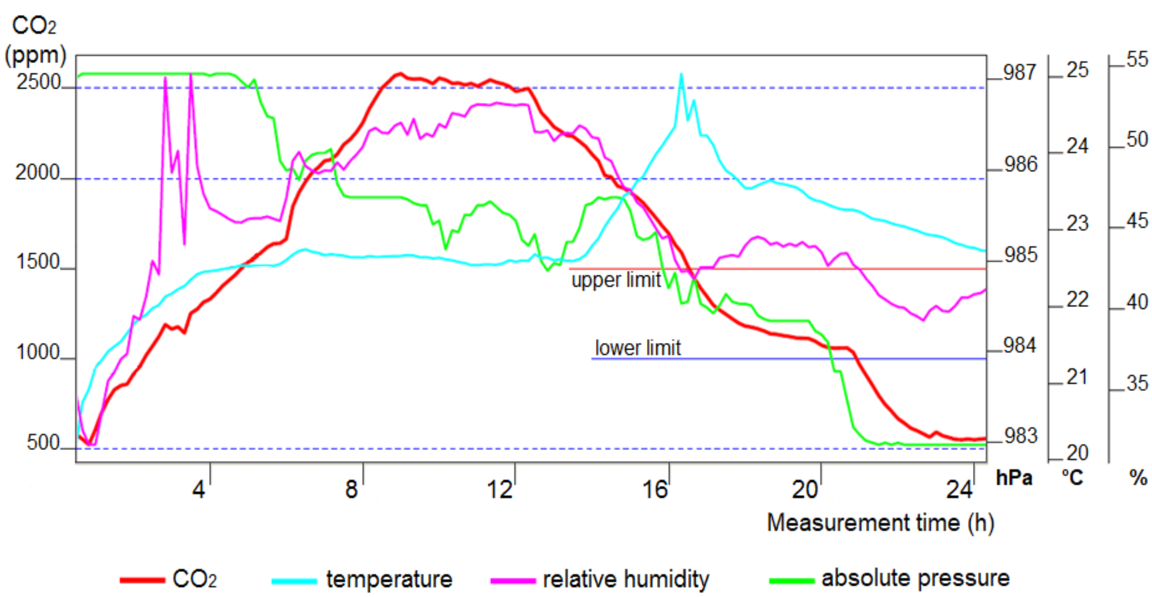

Fig. 6. The course of monitored air quality parameters without controlled ventilation and heat recovery in Květnice

Figure 6 shows monitored values in a family house in the village of Květnice without switched-on controlled ventilation system with heat recovery. According to the CO_2 curve, it is possible to estimate that the users used the bedroom from 7.00 p.m. to 6.30 a.m. The CO_2 value, being the decisive parameter of indoor environment quality, reached above the limit value of 1,500 ppm at 9.30 p.m. and dropped below the limit as late as 10.00 a.m. The maximal CO_2 value was reached at 2.30 a.m. and it was 2,599 ppm. The users left the bedroom at 7.00 a.m. and from that moment, the CO_2 value fluently decreased to the value of 560 ppm. The relative humidity and temperature values were within acceptable limits.

The values with switched-on heat recovery system can be seen in Fig. 7. The graph clearly indicates use of the bedroom from 7.30 p.m. when the CO_2 visibly started to increase to 7.00 a.m. when the decrease can be seen. The CO_2 values reached above the upper limit of 1,500 ppm in the time interval from 12:15 a.m. to 7.00 a.m. The maximal values exceeded the limit value by 180 ppm. When the room was empty, the CO_2 values dropped to 561 ppm. The temperature curve decreased due to heating reduction by the user.

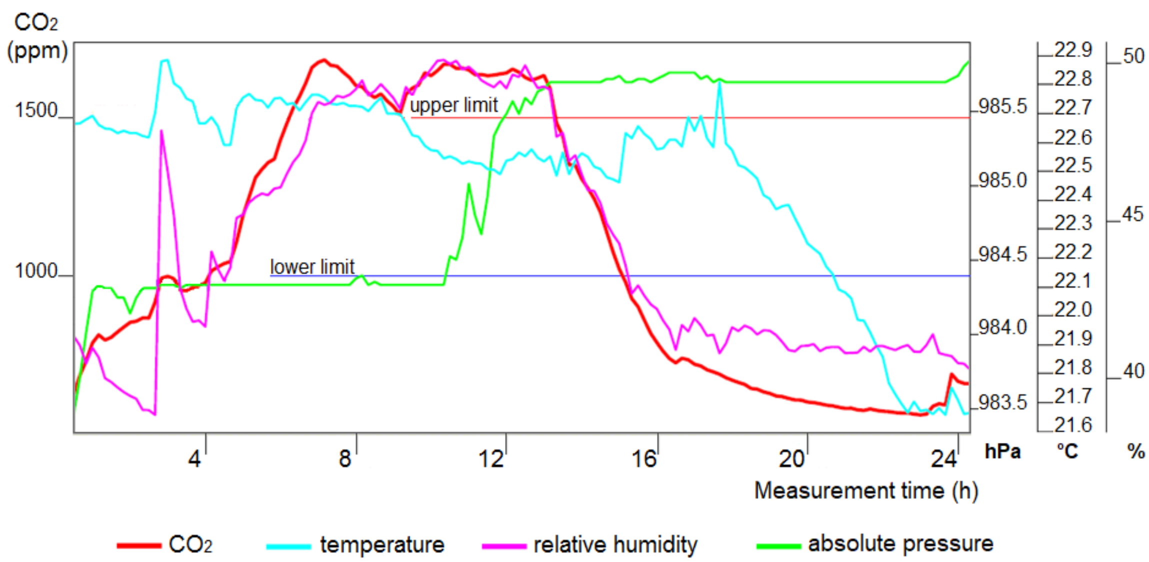

Fig. 7. The course of monitored air quality parameters with controlled ventilation and heat recovery in Květnice

Table 4 indicates the measured medium value of CO_2 without controlled ventilation to reach 1,560 ppm (but with extreme values up to 2,579 ppm), while when using the system it was only 1,067 ppm in the course of 24 h. However, when using controlled ventilation, the maximal value of CO_2 exceeded the maximal recommended value of 1,500 ppm at night by as much as 180 ppm. A simple solution of the high CO_2 levels is installation of CO_2 sensor in the measured bedroom of the parents, similar to the object in Vinoř. In the case of exceeding the pre-set CO_2 limit, the sensor automatically reacts and it increases the power of the unit, allowing better ventilation. The relative humidity values within the measured rooms reached favorable values of about 40%. The ideal summer conditions for residential rooms are as follows: relative humidity: 40 to 55% and temperature: 20 to 23 °C.

Brick house – Prague-Uhříněves

The low-energy brick building, insulated with polystyrene, is made of Porotherm bricks. The measured parameters of air quality from both measuring cycles are stated in Table 5.

Table 5. Measured Values of Parameters at Prague-Uhříněves

		Carbon dioxide (ppm)		Absolute pressure (hPa)		Temperature (°C)		Relative humidity (%)	
Controlled Micro-ventilation		no	yes	no	yes	no	yes	no	yes
Value	minimum	599	448	978	990	20.3	19.7	36.2	25.0
	maximum	5,649	1,130	981	994	27.8	24.9	69.1	37.9
	average	2,704	728	980	992	21.9	21.4	52.8	32.0

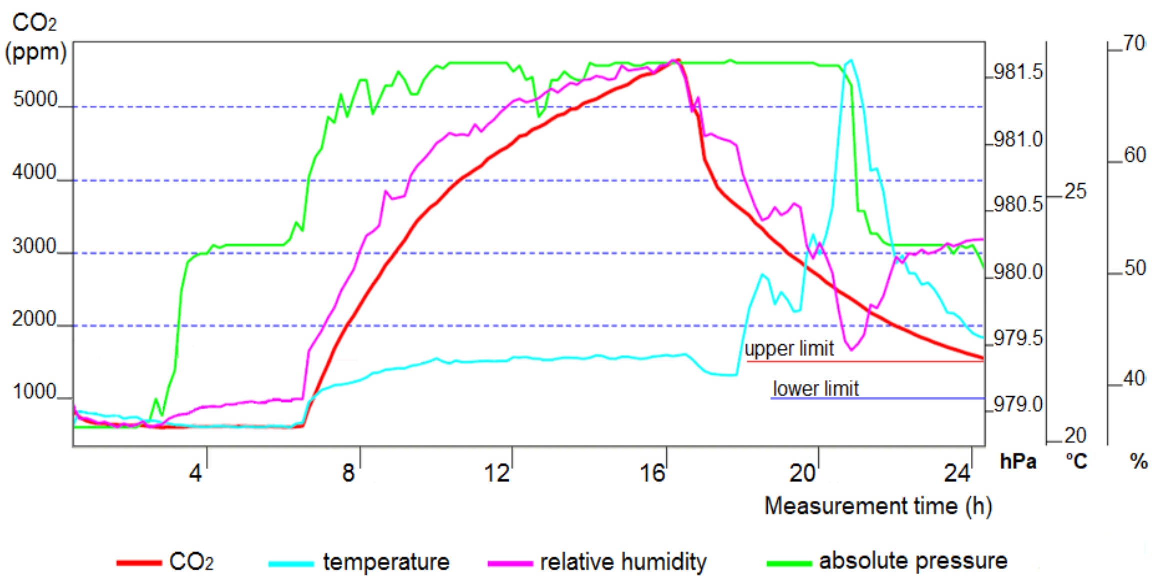

Fig. 8. The course of monitored air quality parameters without controlled ventilation and heat recovery in Prague-Uhříněves

Figure 8 shows the results of indoor environment quality measuring without use of controlled ventilation system with heat recovery in Prague-Uhříněves. The CO_2 curve clearly indicates use of the bedroom by users from 9.00 p.m. From that moment, the CO_2 level quickly increased to the value of 5,649 ppm, which highly exceeded the maximal allowed value of 1,500 ppm. The inhabitants got up at 7.00 a.m. and from that moment the CO_2 value gradually decreased to acceptable values.

Figure 9 shows values with the use of the controlled ventilation system with heat recovery. The CO_2 curve indicates the values when the bedroom inhabitants went to sleep at about 9.00 p.m. and got up at 7.00 a.m. During the entire time of sleeping, the CO_2 value oscillated around the recommended value of 1,000 ppm. When the bedroom was not in use, the monitored value dropped to 448 ppm.

Figures 8 and 9 indicate a temperature increase in the bedroom at about 11.00 a.m. due to heat gains from sunshine; this is due to the south-east orientation of glass surfaces and sunny weather. Along with the temperature increase was a decrease in humidity. The same dependence was established while measuring the wood building in Vinoř.

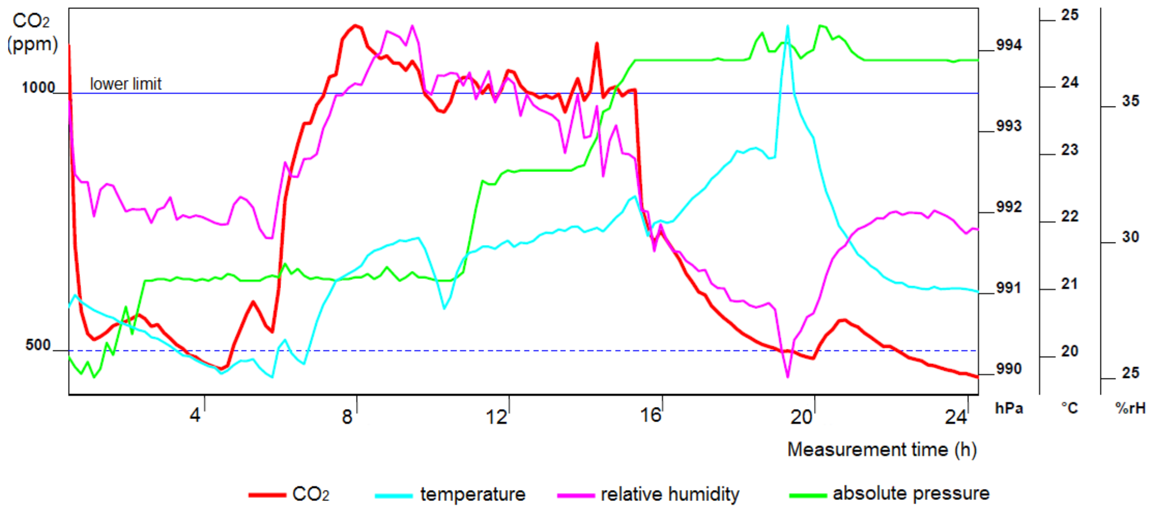

Fig. 9. The course of monitored air quality parameters with controlled ventilation and heat recovery in Prague-Uhříněves

The values obtained in this house indicate significant improvement of an indoor environment using the system of controlled ventilation with heat recovery. Based on Table 4 it is possible to read the medium value of CO_2 without controlled ventilation in the value of 2,704 ppm (but with extreme values up to 5,649 ppm), while when using the system there was a positive value of only 728 ppm in the course of 24 h. The value of 5,649 ppm (Table 4) is not safe for health, and it causes various health problems, such as headache, high pulse, and sickness. When using controlled ventilation, the maximal value of CO_2 did not exceed the maximal recommended value of 1,500 ppm and it reached only to 1,130 ppm. The relative humidity values without controlled ventilation approached the upper limit of recommended values. While using controlled ventilation, the values were successfully reduced to the lower limit of the recommended values.

Concrete Panel Apartment – Prague-Pankrác

The apartment built of concrete panels was the comparison standard, as it is one of the most common types of housing in the Czech Republic. The entire concrete panel house is insulated with polystyrene and it is equipped with plastic windows with double glass. The flat does not have controlled conditioning, and that is why measuring was performed using the plastic windows micro-ventilation. Measurements were performed on the same principle as in the case of wooden buildings and the brick house, *i.e.* the first measuring was performed without micro-ventilation, but in the course of the second measuring, micro-ventilation through windows was provided. The results of both measuring cycles of parameters are presented in Table 6.

Figure 10 represents the values measured in a concrete slab apartment without micro-ventilation. According to the CO_2 value, it is apparent that the bedroom in the concrete slab apartment was used immediately after the device installation, *i.e.* at 10.00 p.m. In the course of the room use, the monitored concentration of CO_2 reached the value of 5,247 ppm. Maximal value was measured at 6:35 a.m. just before the people woke up. Such a volume of CO_2 is, similar to the brick building in Uhříněves without controlled ventilation, high above the limits and deleterious. Rapid decrease of CO_2 was caused by ventilation through windows, as it can be seen from simultaneous temperature decrease. When the people left the bedroom, the CO_2 value was close to the maximal value of 1,500 ppm. That value remained in the room until 3.00 p.m. when one person arrived to stay in the room. Rapid decline of CO_2, temperature, and relative humidity at 6:25 p.m. indicates the room ventilation through windows.

Table 6. Measured Values of Parameters at Prague-Pankrác

		Carbon dioxide (ppm)		Absolute pressure (hPa)		Temperature (°C)		Relative humidity (%)	
Controlled Micro-ventilation		no	yes	no	yes	no	yes	no	yes
Value	minimum	682	565	977	974	21.8	20.8	33.0	41.4
	maximum	5,246	1,897	981	988	24.3	22.9	52.9	50.0
	average	2,290	1,235	979	981	23.6	22.2	44.2	45

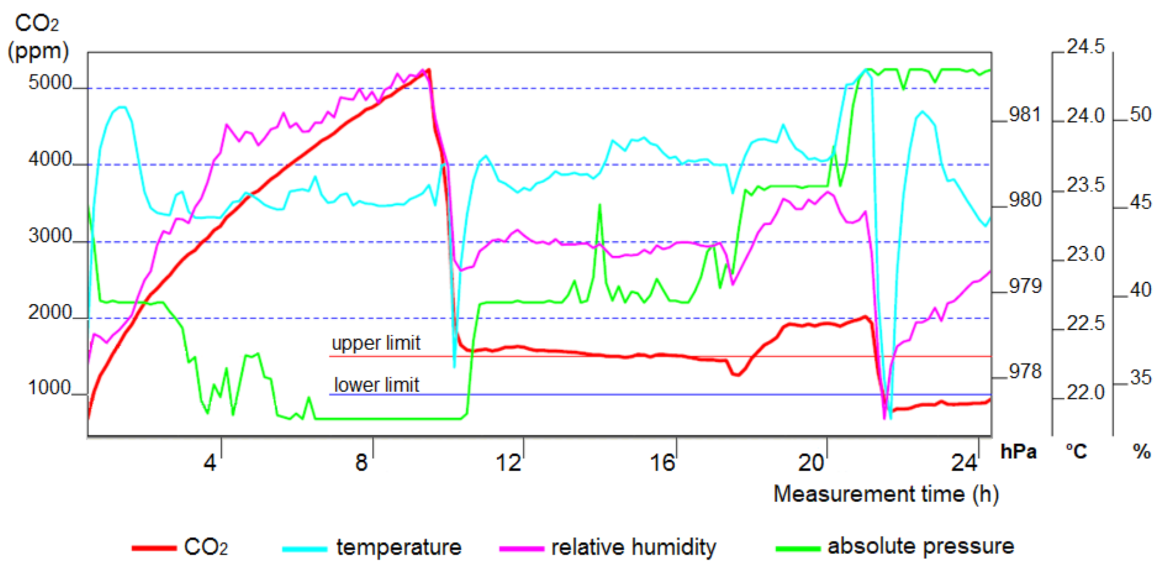

Fig. 10. The course of monitored air quality parameters without micro-ventilation in Prague-Pankrác

The progress of measured data with allowed window micro-ventilation can be seen in Fig. 11. According to the CO_2 value, it is apparent that the bedroom in the concrete slab apartment was used immediately after the device installation, *i.e.* at 9.00 p.m. In the course of sleeping, *i.e.* from the above-mentioned 9.00 p.m. to 6.30 a.m. the CO_2 concentration exceeded the limit value of 1,500 ppm, but not as significantly as in the course of measuring with closed windows. The other values of relative humidity, temperature, and absolute pressure reached acceptable values.

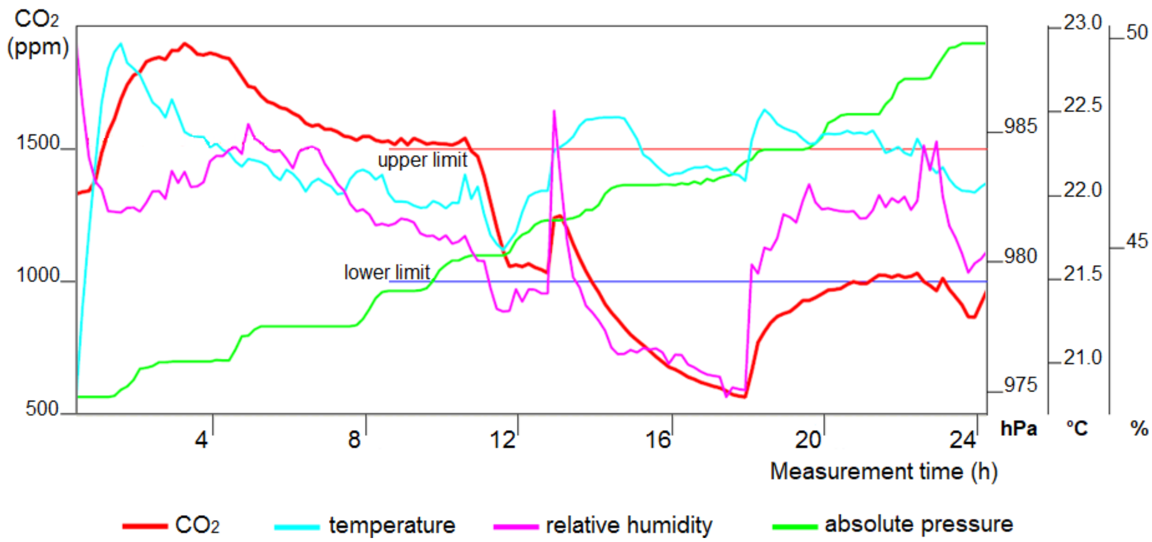

Fig. 11. The course of monitored air quality parameters with micro-ventilation in Prague-Pankrác

Measuring in the apartment was aimed at indoor environment quality with / without use of windows micro-ventilation. A comparison of the graphs indicates the improvement of indoor environment in the case of window micro-ventilation use. Table 4 presents the medium value of CO_2 without ventilation was 2,290 ppm (with extreme values reaching as much as 5,246 ppm) and with micro-ventilation was 1,235 ppm in the course of 24 h. When using micro-ventilation, the CO_2 value exceeded the recommended value of 1,500 ppm at night by as much as 397 ppm. When using micro-ventilation, the average room temperature dropped 2 °C. However, this type of ventilation is not suitable on a long-term basis, due to high heat losses and waste insulation of the object and windows replacement. Relative humidity reached an ideal value of approximately 45% during both measuring cycles.

Table 7. Comparison of CO_2 and Relative Humidity Average Values for All Houses

	CO_2 (ppm)			**Relative humidity** (%)		
House/ Apartment location	Without Ventilation + Heat recovery	With Ventilation + Heat recovery	Difference (%)	Without Ventilation + Heat recovery	With Ventilation + Heat recovery	Difference (%)
Starý Vestec	830	654	-21.2%	36.2	33.8	-6.6%
Vinoř	1,817	1,004	-44.7%	38.9	40.0	2.8%
Květnice	1,560	1,067	-31.6%	45.6	44.3	-2.9%
Prague-Uhříněves	2,704	728	-73.1%	52.8	32.0	-39.4%
Prague-Pankrác	2,290	1,235	-46.1%	44.2	45.0	1.8%

From the point of view of parameters comparison, CO_2 concentration and relative humidity are the decisive factors for indoor environment quality (Tab. 7). Absolute pressure does not change significantly and temperature is regulated by heating to similar level (range between 19 to 25 °C) regardless of the house or apartment construction.

Similar measurements were performed in all the countries, trying to establish unified legislative regulations on the level of national standards, mainly for reconstructions of objects with long-term stay of persons. Other research indicate that multiple exceeding of recommended CO_2 values in residential houses have been established and that air exchange causes a decrease of CO_2 in the range values of 1,359 up to 915 ppm (Kovesi *et al*. 2009), 1,660 to 550 ppm (Wong and Huang 2004), 4,170 to 789 (Zhang *et al*. 2011), 4,630 to 0 ppm (Shendell *et al*. 2004) and in office buildings 1,050 to 440 ppm (Erdmann and Apte 2004), 720 to 410 ppm (Myatt *et al*. 2004), 1,024 to 413 ppm (Federspiel *et al*. 2004).

Within the scope of other similar studies, it has been shown that the highest levels of CO_2 usually occur at night, when the house inhabitants are sleeping. Due to active CO_2 sensors, the measured levels may be below the monitored limit of 1,000 ppm, *e.g.* in the study (Du *et al*. 2016), within the range from 762 to 1,034 ppm.

It would be highly interesting to extend the research so that it would comprise a comparison of structures featuring the same construction and size, including its extension into non-residential buildings, in which several persons are present in one room.

CONCLUSIONS

1. From the point of view of CO_2 concentration, wooden houses are clearly better because even without use of ventilation with heat recovery, the values are much lower compared to brick or concrete slab houses. Without use of ventilation with heat recovery, the average concentration of CO_2 in wooden houses reached 830, 1,817 and 1,560 ppm. A brick house reached an average CO_2 concentration 2,704 ppm, while a concrete slab apartment 2,290 ppm. The use of ventilation with heat recovery significantly affected the CO_2 concentration in all of the monitored houses. In wooden houses, a significant decrease of CO_2 values occurred, and the values approached the recommended limit of 1,000 ppm (654, 1,004 and 1,067 ppm). The decrease was 21.2%, 44.7%, and 31.6% compared to values without ventilation and heat recovery. The CO_2 concentration in a brick house was also significantly lower and it reached the value of only 724 ppm, which was the most significant decrease of 73.1%. In a concrete slab apartment, the average CO_2 concentration was 1,235 ppm, and a decrease of 46.1% occurred.
2. Relative air humidity showed generally lower average values in wooden houses without ventilation with heat recovery, *i.e.* 36.2, 38.9, and 45.6%. The brick house reached the highest average value of relative humidity 52.8%. On the contrary, the concrete slab apartment reached the average value of 44.2%. Ventilation with heat recovery had some influence on relative humidity that changed the least in wooden houses. Decrease of values in 6.6% and 2.9% was recorded in two houses (Starý Vestec and Květnice), while the house in Vinoř showed an increase in 2.8%. The most significant decrease of relative humidity recorded in a brick house reached as much as 39.4%. The concrete slab apartment was affected only minimally, because there was a slight increase of relative humidity in 1.8%.

3. Absolute air pressure was not affected significantly. The influence of ventilation with recuperation did not have any definite character in wooden houses and the differences were really minor (thousandths of percent). Slightly bigger differences were recorded in case of the brick house and the concrete slab apartment, where ventilation with heat recovery caused slight pressure increase.
4. In this case, temperature is the factor that is affected mainly by the needs of house inhabitants, and that is why an exact limit cannot be set. The ventilation with heat recovery did not have any definite character and temperature increases and decreases appeared in the course of the measuring. The difference between average temperature without ventilation and in the course of its operation in wooden houses reached only a few tenths of Celsius degree (up to 0.02%). It was the same in case of the brick house (0.03%). The most significant difference was recorded in the concrete slab apartment, where the difference in temperature with / without ventilation reached 1.4 °C (0.06%).

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