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INDOOR ENVIRONMENT IN BUILDINGS WITH NATURAL VENTILATION

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ŚRODOWISKO WEWNĘTRZNE W BUDYNKACH Z WENTYLACJĄ NATURALNĄ

Jednymi z najważniejszych kryteriów dla oceny budynków jest stan klimatu wewnętrznego i zużycie energii. Silne tendencje do oszczędzania energii skutkują nie tylko stosowaniem lepszych przegród, ale również elementów budowlanych, takich jak okna, charakteryzujących się dużą szczelnością. Jednocześnie, w budynkach nowych oraz istniejących i modernizowanych, stosowane są tradycyjne rozwiązania wentylacji. W takich przypadkach działanie wentylacji staje się istotnym czynnikiem dla realizacji wymagań energetycznych i środowiskowych. Poniżej przedstawiono wybrane wyniki wieloletnich badań. Wyniki te uzyskano drogą badań ankietowych, kompleksowych pomiarów w jednorodzinnych, wielorodzinnych i biurowych budynkach istniejących oraz symulacji komputerowej procesów wentylacyjnych. Celem opracowania jest zaprezentowanie i podsumowanie dużej liczby badań opisujących wpływ wentylacji naturalnej i szczelności przegród na stan środowiska wewnętrznego.

Summary

The most important criteria for evaluation of building engineering is the state of indoor climate and energy consumption. Increase of the rate of energy saving resulted not only in the use of better barriers, but also building elements, such as windows, having low air leakage values. Simultaneously, in the design of new buildings and the retrofit of existing buildings, traditional structures of natural ventilation are used. In these cases, the ventilation is an important tool for a desiderable realization of all environmental and energy requirements. The paper presents selected results of a long-term research work. These results were obtained by questionnaires, measurements and simulations of ventilation processes in typical detached houses, blocks of flats and office buildings. The main objective of the presented paper is to demonstrate investigations and summarize a large number of results which describe the airtightness and natural ventilation on indoor environment.

INTRODUCTION

Major function of buildings is to provide protection for their users from outdoor climate and to maintain acceptable environment, i.e., thermal comfort and indoor air quality. For realization of this aim, the building should fulfill minimal energy demands and should be equipped with efficient heating and ventilation systems. Keeping in mind that buildings are major capital investment and man health is invaluable, the prospect of high energy consumption and poor indoor environment prevailing in them, does contradict their before mentioned functions.

The essential in the design of any heating and ventilation plant is to obtain a comfortable indoor climate, minimizing costs and operating problems [20]. We have become aware of the importance of the indoor climate on human well-being and productivity. This has led to more severe requirements, encouraging manufactures to develop new sophisticated means of control. In theory, these technologies appear adequate to satisfy the most demanding requirements and to provide opportunities for increasing comfort while making substantial energy savings. In practice, however, even the most sophisticated controllers cannot always achieve their theoretical performances. The reason for it is simple: ideal conditions that normally must be fulfilled for their correct operation are not respected. The consequences on indoor environment are not negligible. Especially, this situation can be characteristic for airtight buildings with natural ventilation and obsolete heating systems.

In the last decades, decreased ventilation rates with increased airtightness, resulted in continuous increase of health complaints from building tenants [3, 4, 19, 20]. The set of health symptoms associated with such buildings is called *sick building syndrome* (SBS) and includes nasal, ocular and general diseases. Although exact definition of the cause of SBS is rather difficult, different complaints can be treated as a good index of indoor environment, especially for indoor air quality. According to various studies performed in different buildings, the connection between indoor air quality and the ventilation rate is evident [6, 9, 20]. On the other hand, the ventilation rate is rarely decisive for heat demand, especially in new houses, and, in general, for their energy consumption. Buildings are not only basic consumption goods, but are also space, where people spend considerable part of their lives. Therefore, comfort and health consequences for people working in the offices and living in flats should not be depreciated.

In a naturally-ventilated building, air enters either by uncontrolled infiltration or through provided on purpose openings (like windows), due to the combined action of wind and air temperature differences between the inside and outside of building (stack effect). The process of ventilating in Polish buildings is still realized by means of natural ventilation. Majority of buildings are ventilated through ventilation openings or leaks in the building shell and hardly ever by opening the windows. In these cases, the action of exhaust ventilation ducts is accidental [7–9].

In the past, the coefficient of airtightness for windows varied between 3 and 6 m^3/mh at 1 daPa. According to the New Polish Standards, this coefficient is 0.5 m^3/mh at 1 daPa or 1.0 m^3/mh at 1 daPa. Recently, the majority of windows have been tight and coefficient rarely has lowered to 0.5 m^3/mh at 1 daPa. Building tightness without providing proper ventilation can cause health and safety problems. Higher moisture levels found in inadequately ventilated buildings create proper environment for molds, dust, mites, CO_2 concentration and cause respiratory problems and allergies [1]. Tighter buildings are also more likely to experience problems from backdrafting and spillage of combustion products from naturally drafting furnaces, water heaters and other fireplaces [15, 16, 21]. All buildings need supplies of outdoor air, not only for the comfort and health of occupants, but also for the control of condensation and efficient operation of combustion appliances.

OBJECTS AND METHODS OF INVESTIGATION

The survey was carried between the years1998 and 2000 and dealt with blocks of flats (BF – six buildings), detached houses (DH – four objects) and office buildings (OB –

four objects) located in the southern areas of Poland [8, 10–12]. Examples of view of these buildings are shown in Figure 1. The height of all blocks (BF) and office buildings (OB) is similar and equals 18 m (4 storeys) and it is about 7 m for detached houses (DH – 1.5 storeys). The indoor volume for BF and OB is about 5000 m^3 and for DH – 455 m^3. The ratio of gross enclosure area to these volumes is 0.62/m (for BF), 0.65/m (for OB) and 0.98/m (for DH). The blocks of flats and office buildings are located nearby the city area and built from hollow masonry units and prefabricated panels. The office buildings are not thermo modernized and their shells are thermally insulated according to the old standard requirements with the overall U-value of about 1.5 W/m^2K (solid walls – 0.8–0.9 W/m^2K). Blocks of flats and detached houses are after modernization and their shell is thermally insulated according to new standards. The U-value for solid walls varies between 0.5 and 0.7 W/m^2K. In the majority of flats new and tight windows are applied (with wooden or plastic frames). Similar values are in detached houses. The object's heat demands are covered by two-pipe central heating systems with thermostatic valves (BF) or without them (OB and DH). These systems are supplied by the heat generating plant (by thermal heat distribution centre located in the cellar of BF and OB or by the gas boiler in detached houses.

All buildings are naturally ventilated with individual (1 in Fig. 1) or collective ducts (2 in Fig. 1). Blocks of flats and detached houses are equipped with gas stoves for preparing meals and boiling hot water (3 in Fig. 1).

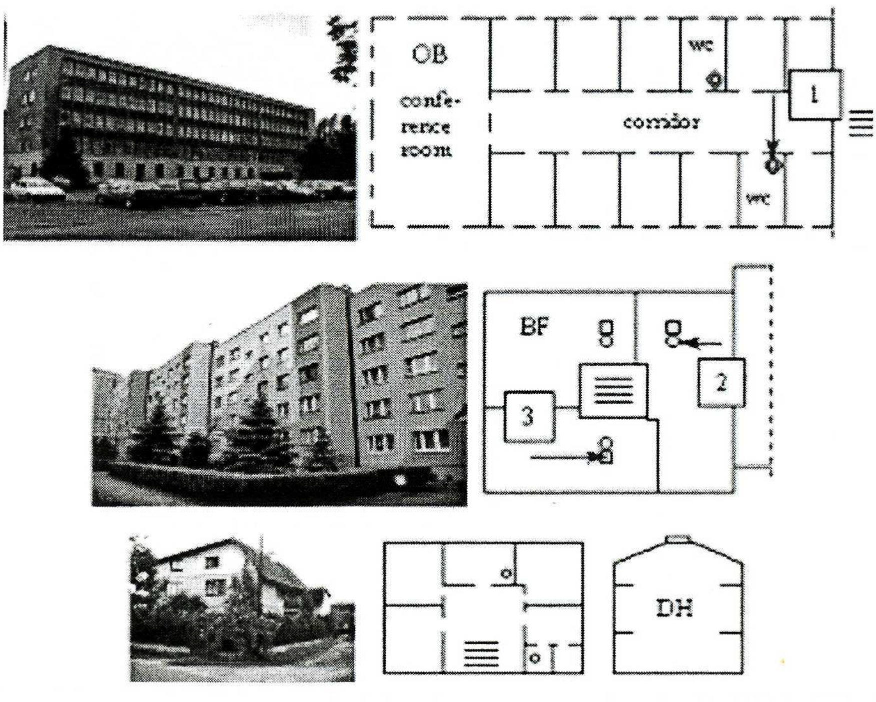

Fig. 1. View and the floor plan of tested buildings
Notations: OB – office building, BF – block of flats, DH – detached house, 1 – individual ducts, 2 – collective ducts, 3 – exhaust gas ducts (combustion gas)

A way to acquire data about the occupants comfort was gathering information from questionnaires. Two types of questionnaires were used. The first type comprised questions about thermal comfort, ventilation system functioning in particular rooms and risk connected with the indoors emissions. The questions also concerned living conditions in flats, working conditions in offices, the age of occupants, health and smoking habits, dust, odor, temperature, humidity, air velocity, etc. The basic questions were: 1° – Do you find the air in the room – hot, warm,..., cool, cold ?, 2° – Do you find the quality of the air satisfactory ... unsatisfactory ?, 3° – Is the air dry or humid ?, 4° – Is the indoors climate comfortable or uncomfortable ?, etc. The second type of questionnaire was completed by professional auditors, upon their arrival to the building. Principles of these questionnaires are based on the European proposition presented in Finland NT-Report [8, 15]. In this type of questionnaire nineteen health symptoms were determined.

In order to evaluate the effects of ventilation, some research was taken. The indoor climate can be mainly characterized by the temperature and relative humidity of internal air, concentration of carbon monoxide and carbon dioxide, concentration of nitrogen dioxide, formaldehyde and ozone and also the ventilation rate. This rate is also necessary for calculation of energy consumption [9–11]. The instrumentation used in measurements is compared in Table 1.

Table 1. Characteristics of measuring instrumentations

Property	Instrument	Accuracy
Air temperature	VT 300/MM-01/KIMO instruments/Aereco	± 0.5 up to 50°C
Relative humidity		± 2% of the measured value
Air velocity		± 0.02 m/s + 5% of the measured values
Pressure difference		± 0.5 up to 100 Pa
Concentrations		
CO_2	Carbon Dioxide Monitor – Model 2006-SP	± 50 ppm up to 10000 ppm
	Solomat MPM4100 – Brandt instruments/Zellweger Analytics of Lincolnshire	±1 ppm to 5000/3000 ppm
CO	Electrochemistrymeter Tox CO/ANA/EC	± 1% of the measured value up to 200 ppm
NO_2 and O_3	Spectrophotometer – UV-2101 PC/SHIMADZU	± 1 mg/m^3 (± 5%)
Formaldehyde	Chromatograph – HP 5890 (FID detector)	± 1 mg/m^3 (± 10%)

To determine the air leakage values for windows and doors, the pressurization tests were applied with the use of plastic cover tightly taped to the window and door frame (the small-scale tests). In these cases, chamber tests were used (Fig. 2). The fan inlet was connected to the tested chamber by a duct of about 1.5 m length and 0.2 m in diameter. The chamber was made of plywood panels covered wit polyethylene sheets and was sealed with a tape around the perimeter of tested element. Air flow rates of the fan were measured with an adjusted damper (accuracy of 10% of measured values). Pressure differences that proceed across the middle of element were measured with a diaphragm-type pressure transducer and digital voltmeter (static error band o 5% of the scale) [8–10].

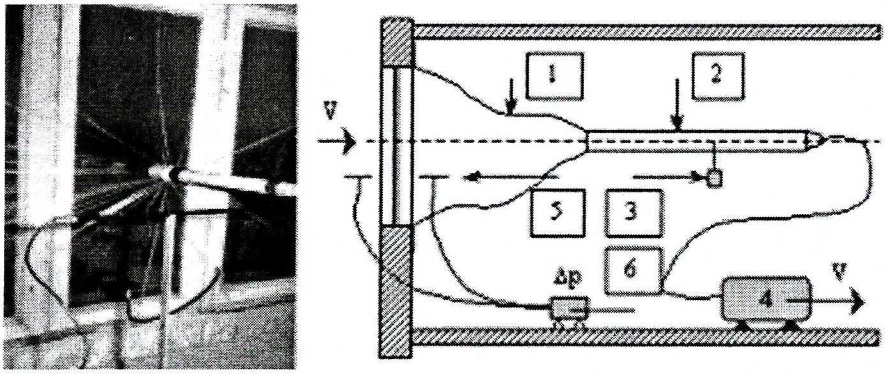

Fig. 2. Scheme of the experimental stand for determination of the leakage values (for windows and doors)
Notations: 1 – test chamber (in the photograph), 2 – duct, 3 – a hot-wire of anemometer, 4 – fan, 5 – pressure difference, 6 – micromanometer

There were also large-scale pressurization tests applied in selected rooms, flats and offices. Two types of stands and two methods were used. In the first type, the fan used was vane axial type with a variable-pitch blade that could be adjusted manually to obtain flow rates between 0 and 3 m^3/s. The fan inlet was connected by the duct of 0.4 m in diameter. The entrance door was replaced by a plywood panel for the tests (upper side of Fig. 3). Tested spaces were pressurized, with the pressure differences from about 10 Pa to 100–120 Pa at increments of about 10 Pa. There was also air flow measured in the spaces, required to maintain each pressure difference. The second type of test method used at the stand, was the pressurization or depressurization of space with a fan previously calibrated, made of plastic and fixed in a door (lower side in Fig. 3) [6, 8, 10, 12, 13]. The first and second methods show pressure differences created by the fan between the inside and outside space. The known airflow rate induced by the same space envelope, and the measured differences are expressed by the equation: $V = K(Dp)^{\alpha}$. So the tests must be done for several Dp, usually between 10 and 100 Pa in order to obtain air coefficients K and α by means of statistical analysis. The same way for analysis of the small-scale tests′ results was used. A similar method was used for detached houses (Fig. 4). The accuracy of these tests is about ± 8%.

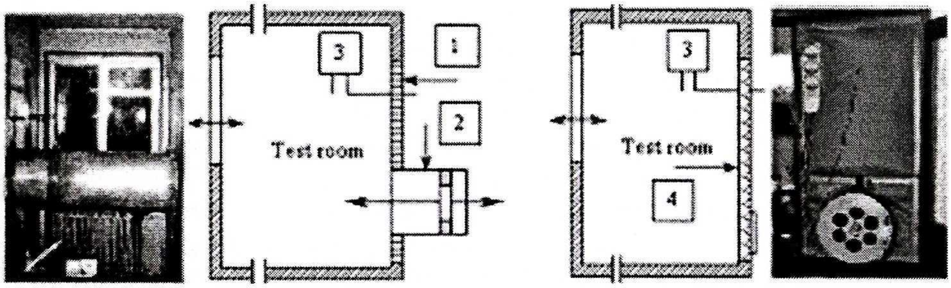

Fig. 3. The schematic diagram of large-scale pressurization test (for flats or rooms in BF and for offices in OB)
Notations: 1 – additional door with a duct, 2 – duct with a fan (in the photograph), 3 – pressure difference, 4 – the Minneapolis Blower Door (in the photograph)

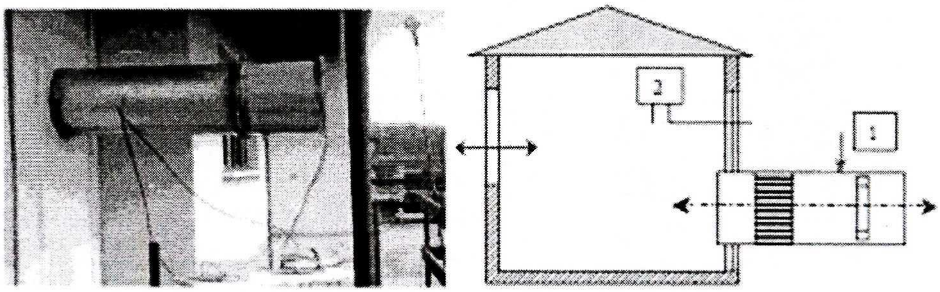

Fig. 4. The view of large-scale pressurization test (for DH)
Notations: 1 – special duct with a fan and a hot-wire anemometer (measuring of velocity and air quantity), 2 – micromanometer (pressure difference)

The ventilation rate for a flat or particular room was measured by using gas technique with carbon dioxide as the tracer. Carbon dioxide was released by injection samples in the centre of tested space. Every 15/20 minutes after the tracer release, a sample of the indoor air was taken to the analyzer with a logger (Air Tech 2006/SP with accuracy ± 50 ppm up to the 10000 ppm). A simple scheme of this stand is shown in Figure 5. The average CO_2 concentration was about 5000 ppm (maximum 8500 ppm). This measurement lasted 5–8 hours. The concentration changes were recorded and then the ventilation rates were calculated. The accuracy of the measurement was about ± 2–3%.

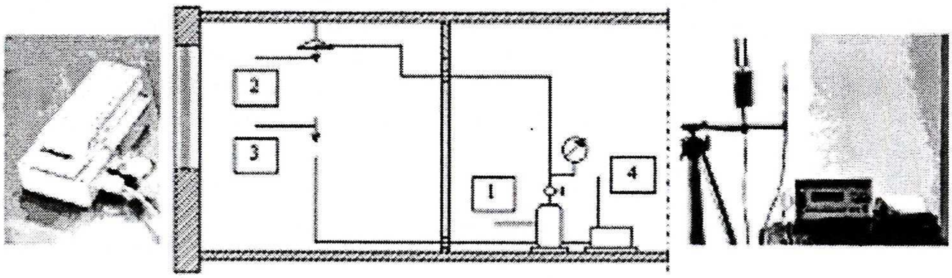

Fig. 5. Scheme of the measuring stand (a gas technique for flats and rooms)
Notation: 1 – a gas tank (6 m^3 CO_2), 2 – sample of gas inlet, 3 – sample of gas outlet (to the meter 4), 4 – meter of CO_2 concentration in indoor air – Air Tech 2006-SP (with data logger – in the photographs)

In selected rooms and offices daily carbon dioxide concentration was also measured (by Solomat MPM4100/PS 30), and external parameters influencing air flows were recorded (outdoor temperatures, wind velocities and its direction, etc.). At the same time, the measurements of CO concentrations were also carried out (by Tox-CO). These measurements were performed in the periods of bathrooms exploitation and meals preparation in kitchens.

Because measurements could only be made over a limited time, they were, therefore, representative for only a small range of weather conditions. Various measurement data were used as the input to numerical simulation so that a broader range of results for varying weather conditions could be established [11, 17]. Therefore, in the next stage of investigation air change in the buildings was calculated. Two types of methods were used. The first method was a sample analytical model of building (single-zone) such as Infiltration and Air-1 [9, 14]. The second method was a multi-zone model (network method). These analyses were performed with help of author's program a Symvent and AirSym [10, 13]. The next part was the detailed simulation of air flows and concentration of carbon monoxide and carbon dioxide in rooms located in selected flats. These analyses were obtained with the help of the NIST code *Contam* [18]. Some results of measurements and simulations are presented and discussed below.

SELECTED RESULTS OF INVESTIGATION

Results of small-scale pressurization tests for windows and main entry doors are presented in Figure 6. On an average, the air coefficient for all windows is about 0.06 dm³/ms at 1 Pa and for door – 0.12 dm³/ms at 1 Pa (or 1 m³/mh at 1 daPa and 2 m³/mh at 1 daPa).

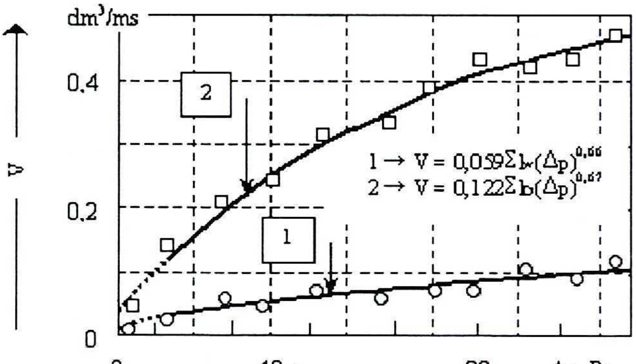

Fig. 6. Results of small-scale pressurization tests for windows (1) and doors (2)

For windows these values are compatible to the new Polish requirements. However, the most representative for the evaluation of room tightness were results obtained by means of one of large pressurization tests, and particularly – gas techniques. Example results of such investigations are presented in Figure 7. These results concerned 22 flats located in one of the tested blocks. On an average, the airtightness of external walls after modernization was about three times higher than before it (0.0032 ® 0.0012 m³/s at 1Pa). In this situation, the mean air exchange decreased from 1.1/h to about 0.3/h. Intensity of air flows in tested

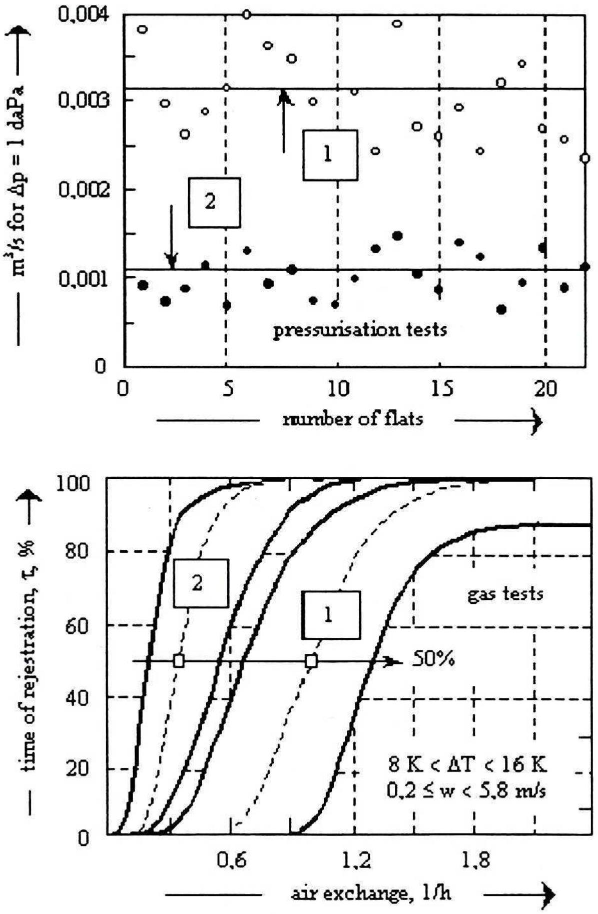

Fig. 7. Results of pressurisation (upper diagram – for: -2°C < t_e < +10°C and w < 4.2 m/s) and decay of gas tests in one of examined block of flats
Notations: 1 – before thermo modernization, 2 – after thermo modernization

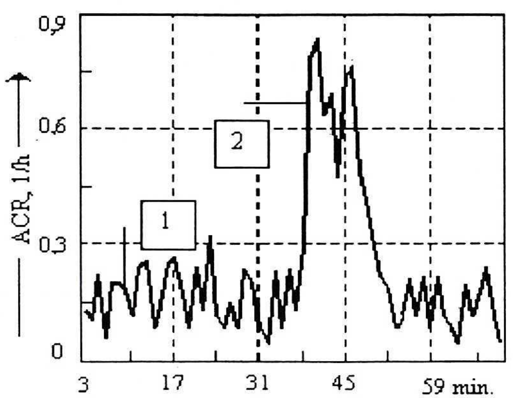

Fig. 8. Influence of partly opened windows as the result of tracer gas decay method
Notation: 1 – open in 3%, 2 – as above but in 15% (for 0°C < t_e < +12°C and w < 5.1 m/s)

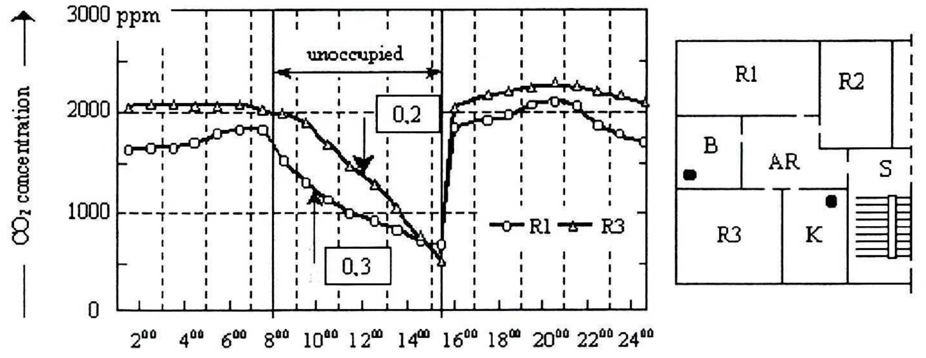

Fig. 9. CO_2 concentration in a typical winter day for two rooms (t_e ~ 0°C, w ~ 0.3 m/s) Notations: R1 and R2 – rooms (look also in Fig. 16).

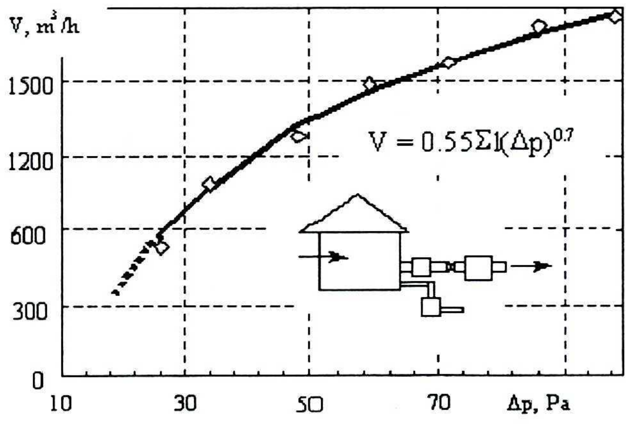

Fig. 10. Results of pressurization test in one of detached houses with new windows (for ΔT ~ 15K and w < 0.8 m/s)

rooms can be increased when windows are partly opened. Representative data for such a situation for one of the rooms are presented in Figure 8. When the windows were closed, the air change rate values corresponded to the absence of air flows. When the windows were partly opened, the air exchange increased to 0.6–0.8/h (windows opened in about 15%) and even to 1.6–2.7/h (windows opened in 30%). The ventilation rate in a flat was also determined on the basis of a test (Fig. 9). This rate was about 0.2/h. The representative data for a detached house is presented in Figure 10. The average air change rate for theses houses varied between 0.15/h and 0.25/h. Simultaneously, the air leakage coefficients for windows were about 0.03 dm^3/ms at 1 Pa (or 0.55 m^3/mh at 1 daPa).

The influence of the ventilation process on concentration of selected contaminants (dioxide nitrogen, formaldehyde, ozone, etc.) was measured in all buildings. The comparison of these concentration values is presented in Figure 11. Mean I/Q ratios (indoor/outdoor) estimated for different rooms were always above 1, especially for HCOH and CO (Tab. 2). When the rooms were unoccupied, the I/Q ratios were a little higher than 1 (probably because of the absence of majority of indoor disturbances). For example, when people were in rooms, the ratio I/Q for formaldehyde varied between 5 and 16. The indoor concentration of carbon dioxide depended on the outdoor level of CO_2 and its production rate within space under investigation. In offices, this extra contribution was assumed to result from metabolism and smoking, but in blocks of flats and detached houses gas cookers and other indoor sources could make further significant contribution. To determine the generated CO_2, the difference between its indoor and outdoor concentration should be measured. Approximately, its outdoor level of 380–410 ppm was usually assumed. Figure 12 presents CO_2 concentration in one of tested offices. As shown, an average CO_2 concentration per hour varied between 410 ppm when the office was not occupied and about 3000 ppm at occupied hours. Maximum CO_2 concentration values were monitored when all occupants were smoking. The changes illustrated in Figure 13 are representative for rooms located in blocks of flats. In this case, the concentration of CO_2 varies also between 400 ppm and about 3000 ppm (or higher). Simultaneously, average CO concentration values for intensely used bathrooms were 20–25 mg/m^3 (maximally 40 mg/m^3). In kitchens they were several times smaller than in bathrooms (8–10 mg/m^3). In both cases, however, these values were larger than standard ones (3–6 mg/m^3).

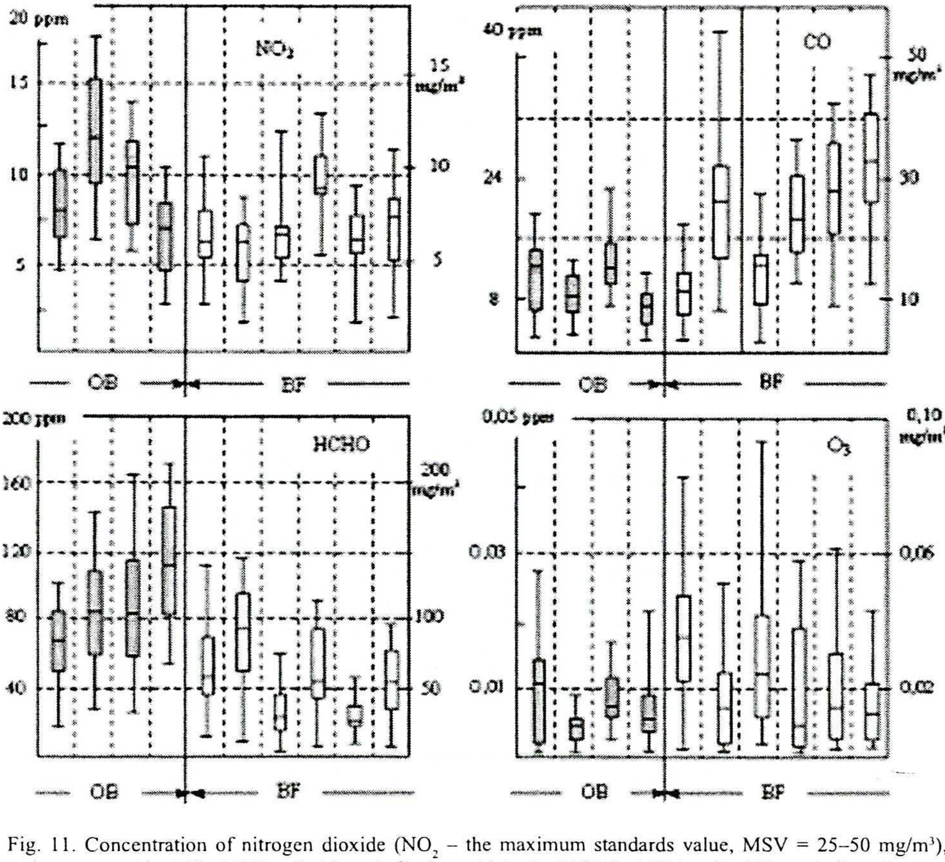

Fig. 11. Concentration of nitrogen dioxide (NO_2 – the maximum standards value, MSV = 25–50 mg/m^3), carbon monoxide (CO, MSV = 3–10 mg/m^3), formaldehyde (HCHO, MSV = 50–100 mg/m^3) and ozone (O_3, MSV = 100–150 mg/m^3) in tested buildings

Table 2. The average I/O ratios for typical conditions

Type of pollutant	Ratio of indoor/outdoor									
	Blocks of flats						Office Buildings			
	1	2	3	4	5	6	1	2	3	4
Carbon dioxide (CO_2)	1.34–7.55						1.02–1.94			
Formaldehyde (HCHO)	4.7	11.8	6.1	9.3	10.8	7.2	12	15.5	9.6	14.8
Nitrogen dioxide (NO_2)	1.4	0.9	3.1	0.9	1.7	1.3	1.3	1.0	1.7	2.5
Ozone (O_3)	1.2	1.8	1.2	1.1	1.0	1.1	1.7	1.4	2.1	1.8

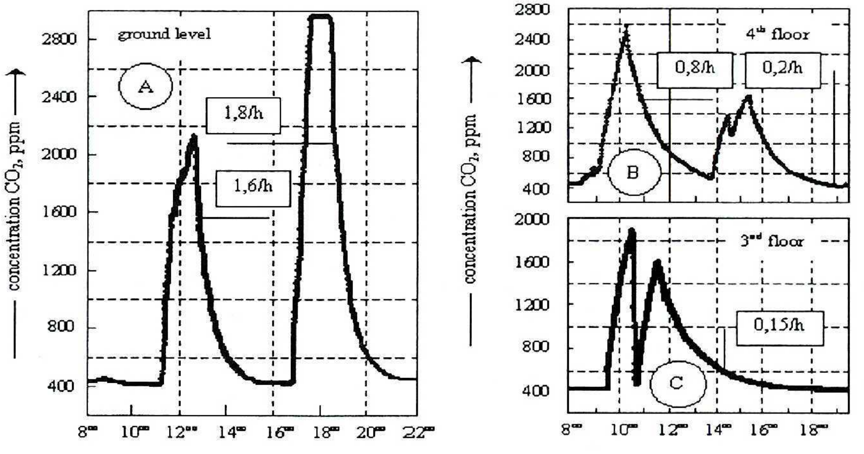

Fig. 12. Temporal variation of CO_2 during the period of measurements for three offices in their typical operational use (in winter conditions)
Notations: A – old windows and smoking fumes, B – tight windows and smoking fumes, C – with tight windows and without smoking

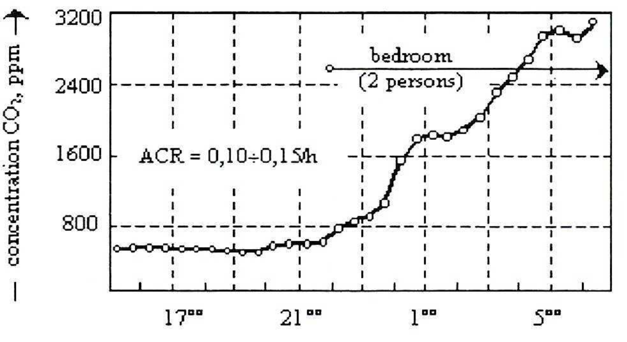

Fig. 13. Change of CO_2 concentration in room with tight windows located on 2nd storey in 4 storeyed building with tight windows (in winter conditions)

Out of 3523 respondents, 2982 (about 85%) participated in surveys. About 55% of the occupants were younger than 50. Among the entire population 33% were between 20 and 40 years old and 12% younger than 10 (children). As far as sex and age are concerned, 35% of women were between 25 and 35, 45% of them were younger than 50. The analysis of questionnaires showed general dissatisfaction of the occupants with all the parameters they had been asked to evaluate. Figure 14 details their responses. The range of air temperatures and relative humidities in the winter season is presented in Figure 15. On an average, 17–58% (in flats) and 32–47% (in offices) of occupants complained about hot or cold indoor air. The percentage of occupants complaining about relative humidity was also significant, since most complaints were about the dryness of air (17% and 46%). Majority of respondents were dissatisfied with ventilation (in blocks of flats even about 80% – Fig. 14). The results referring health symptoms reported by the employees in examined types of buildings are compared in Table 3. As shown, majority of complaints concerned especially such symptoms like headaches, dizziness, eye irritation and unusual fatigue. Respondents also reported relatively high frequencies of allergies, asthma and bronchitis. High percentage of respondents reported dissatisfaction with a number of physical environmental parameters such as air movement and dust. It is proper to emphasize that using gas devices (especially – water gas heaters), often caused nausea leading to vomiting. The occurrence of above-mentioned symptoms per person was slightly higher in blocks of flats than in detached houses and office buildings.

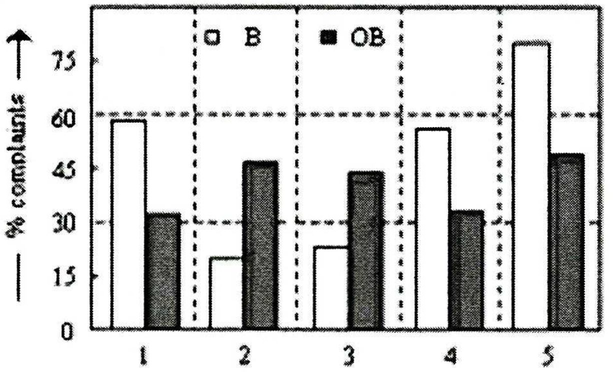

Fig. 14. Complaints concerning selected parameters (B = BF + DH)
Notations: 1 – hot, 2 – cold, 3 – dry air, 4 – wet air, 5 – bad ventilation (lack of fresh air)

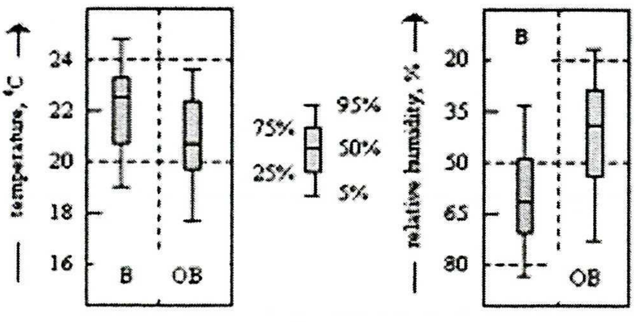

Fig. 15. Air temperatures and relative humidities in tested buildings (B = BF + DH)

Table 3. Health symptoms and their occurrences reported by occupants

Symptoms		Blocks of flats and detached houses (1641 respondents)	Office Buildings (1370 respondents)
1	Eye irritation	229 (14.2%)	522 (38.1%)
2	Dry/sore infection	42 (2.6%)	118 (8.6%)
3	Irritation cough	156 (9.7%)	173 (12.6%)
4	Excessive phlegm	206 (12.8%)	595 (43.4%)
5	Sinus infection	98 (0.9%)	45 (3.3%)
6	Bronchial pneumonia	132 (8.2%)	174 (12.7%)
7	Asthmatic attacks	127 (7.9%)	126 (9.2%)
8	Headaches	714 (44.3%)	947 (69.1%)
9	Dizziness	585 (36.3%)	811 (59.2%)
10	Unusual fatigue	587 (36.4%)	580 (42.3%)
11	Difficulty in sleeping	164 (10.2%)	—
12	Nasal irritation	205 (12.7%)	545 (39.8%)
13	Nosebleed	55 (3.4%)	99 (7.2%)
14	Nausea	181 (11.2%)	207 (15.1%)
15	Vomiting	203 (12.6%)	3 (0.2%)
16	Abdominal irritation	29 (1.8%)	60 (4.4%)
17	Whole body ache	102 (6.3%)	264 (19.3%)
18	Fever	47 (2.9%)	130 (9.5%)
19	Stuffy/"bad" air	123 (7.6%)	188 (13.7%)

Information about conditions inside the building was obtained also by computer simulation. Some results of investigation for flat and rooms located on the ground level of blocks (Fig. 16) are presented below. Assumed air leakage coefficients for all windows were about 1 m^3/mh at 1 daPa and for doors – 2 m^3/mh at 1 daPa (according to the rules of Polish Standards and to results of measurements – Fig. 6). Natural (gravitational) ventilation was used in calculated buildings. Ventilation was performed by individual ducts of each flat (0.14×0.14 m). The inlets of ventilation ducts are located in kitchens and bathrooms. Time and place where occupants stayed and the level of emitted carbon dioxide (metabolically) was established according to the assumed lifestyle of residents (as the results of questionnaires and measurements) [7]. These assumptions are gathered in Table 4. Meteorological data used in simulation, based on real climate (for heating season in Katowice).

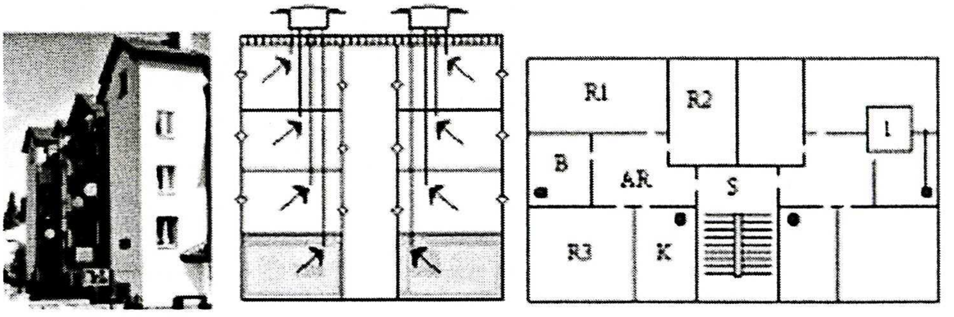

Fig. 16. View and internal layout with selected section of simulated building
Notations: R1, 2, 3 – rooms, B – bathroom, K – kitchen, AR – anteroom, S – stairway, 1 – ventilation ducts

Table 4. Time profiles for used rooms

	Hours of day																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
I	R1					B	—									R1					B	R1		
II	R1					B	—									K	R1				B	R1		
III	R3						B	—							R3		R1		B	R3				
IV	R3						B	—							R3		R1		B	R3				
V	—											R2			R3	K	—							

I – adult person (weight W = 80 kg) and emission of $CO_2 \rightarrow E = 10 \times 10^{-6}$ m^3/s, II – as above (W = 60 kg) and $E = 10 \times 10^{-6}$ m^3/s, III - children (W = 45 kg) and $E = 6 \times 10^{-6}$ m^3/s, IV – as above (W = 35kg) and $E = 6 \times 10^{-6}$ m^3/s, V – adult person (W = 60 kg) and $E = 10 \times 10^{-6}$ m^3/s

The first groups of simulation results are these referring to air exchange of the whole flat. Figure 17 shows time-variables of air flow into flats located on the ground level on 3rd floor. The average values of air change rates for January give about 0.13/h (for a flat located on 3rd storey) and 0.42/h (for a flat located on the ground level). These values are lower than the standard value (1/h). The changeability of air flows through selected rooms in a flat located on the ground level of tested blocks are presented in Figure 18. This picture is characteristic for all blocks of flats with natural ventilation. Typical abnormalities in tested cases were backflows in one of the ducts. The studied case concerned the kitchen duct (V_{OK} in Fig. 18). In other flats the picture of air flows was more unfavorable. Air flows in these flats and rooms corresponded with a lack of air change rate. In these cases, the personal ventilation rate varied between 0.58 dm^3/s (for room R1 and 1.15 0.58 dm^3/s (for room R3) and was lower than required value (about 5.5 dm^3/s). Simultaneously, average values of carbon dioxide concentration in tested rooms varied between 3000 ppm and 5000 ppm (Fig. 19). This is the effect of excessively tight windows.

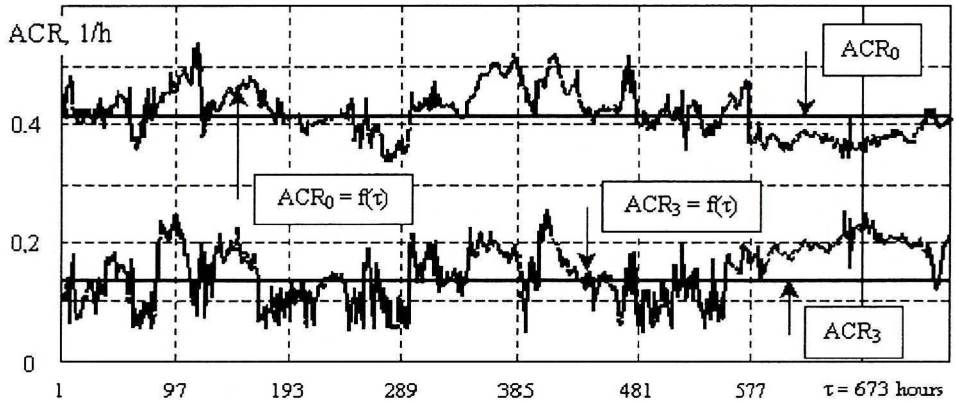

Fig. 17. Run of ventilation rate in chosen flats of the building (the air leakage coefficients for windows are 1 m³/mh at 1 daPa or 0.06 dm³/ms at 1 Pa)
Notations: ACR_0 and ACR_3 – the air change in the flat located on the first and top storeys

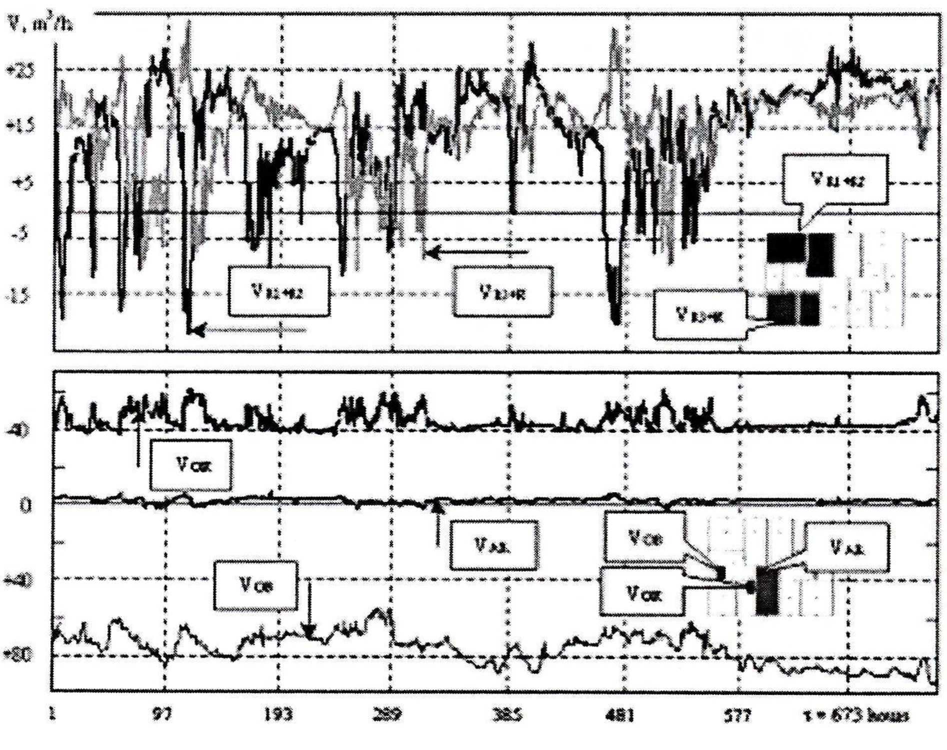

Fig. 18. Hourly run variation of air flows in the flat on the first storey of tested building for January (the air leakage coefficients for all windows are 1 m³/mh at 1 daPa or 0.06 dm³/ms at 1Pa)
Notations: $V_{R1\div R2}$, $V_{R3\div K}$ – air inlets through gaps in windows, V_{AR} – as above but through gaps in the door (from the stairway), V_O – air outlets by natural ventilation ducts (from the kitchen – V_{OK} and bathroom – V_{OB})

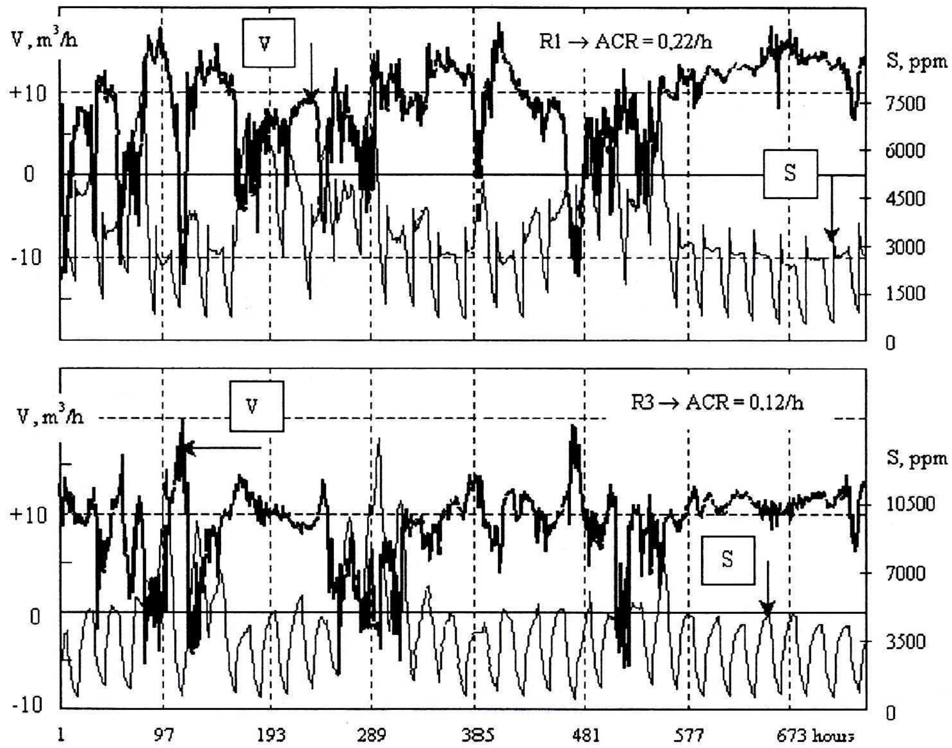

Fig. 19. Changeability of air flows (V) and CO_2 concentrations (S) for two rooms (R1 and R3) and the leakage coefficients for all windows ® 1 m³/mh at 1 daPa or 0.06 dm³/ms at 1 Pa (January)

Comparatively large CO_2 concentration causes removing of the oxygen from the air. This condition creates incomplete processes of burning in gas devices. Main danger in the flats equipped with home gas devices is a periodical rise of concentration of partial gas combustion products (mainly CO and NO_2), and its free migration in rooms, flats and buildings. Some results of simulations were made for 4-storey block of flats, equipped with ventilation ducts providing natural ventilation, gas passes and typical gas cookers (each equipped with four burners and baking oven), and water heaters (in bathrooms). They were analyzed with the help of the *Contam* program. The following temporary profiles of use of these gas accessories were (assuming their ideal state): for water heaters – 7^{00} am – 8^{00} am; 3^{00} pm – 5^{00} pm; 8^{00} pm – 10^{00} pm and cookers – 7^{30} am – 8^{00} am; 3^{00} pm – 4^{30} pm; 7^{00} pm – 7^{30} pm [7]. The variable airtightness of building woodwork was also considered (from 0.3 to 3 m³/mh at 1 daPa – ventilation openings in windows were not applied). The study covered changing climate parameters recorded every hour: the temperatures, velocity and directions of wind as well as concentrations of CO and NO_2 in outdoor air. Computations were made to estimate combustion products mentioned previously and their migration inside considered buildings. The data presented in Figure 20 describe the concentration of pollution factors for kitchens and bathrooms located in one of building's vertical sections. In bathrooms this concentration was several times higher than in kitchens. The increase of pollution concentration inside these rooms depending on height of the building could be observed.

Such changes also appeared for variable weather conditions and depended on window tightness. The data presented in Figure 21 confirm this assumption. Because of the high correlation of both analyzed kinds of pollution (i.e., CO and NO_2), estimation of their concentration was replaced with the estimation of CO concentration only. Presented data show the dependence of correlation coefficient on airtightness, represented by values of air penetration, which is considerably strong. High tightness of windows resulted in the raise of pollution concentration. But it does not appear always. For example, the maximal CO concentration can accompany medium value of airtightness (i.e., 1 m^3/mh at 1 daPa) in flats located on the highest storey and it can happen often. There are many factors and parameters that act at the same time, influencing the air exchange inside buildings and it should not be forgotten. So it can be assumed that usually the dangerous raise of pollution factors happens in transient periods with high velocity winds and their variable directions (spring, autumn). Time periods of these uncomfortable conditions lengthen considerably in the case of buildings located in valleys and on hills or areas of compact building development, e.g., town centers. It is obvious from presented results that dangerous conditions for people living or working in considered buildings last for 150–200 hours a year, on an average [8, 10, 11]. It means that there is high risk of health hazard for about 75% of the year for people living in these buildings.

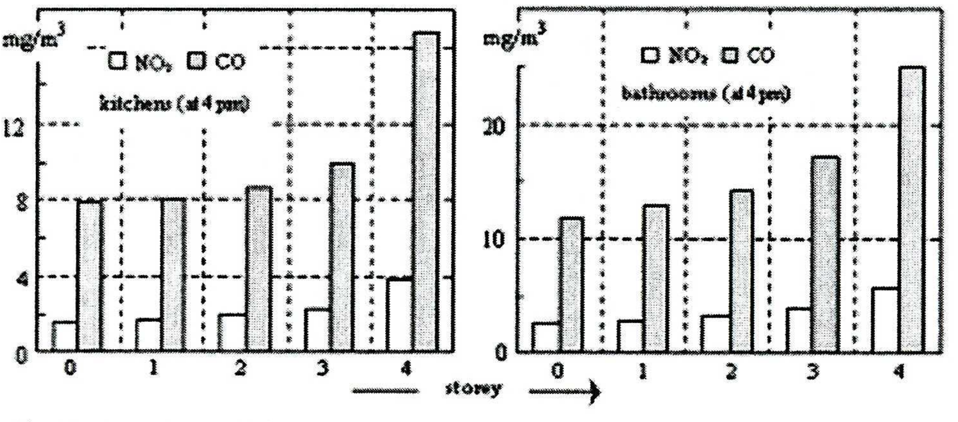

Fig. 20. Concentration of nitrogen dioxide (NO_2) and carbon oxide (CO) in kitchens and bathrooms (the air leakage coefficients for all windows are 0.02 dm^3/ms at 1 Pa or 0.3 m^3/mh at 1 daPa)

Obtained results can be used for prediction of dangerous situations caused by the presence of toxic carbon monoxide in the indoor air. In insufficiently ventilated rooms from gas devices pollution (mainly in bathrooms without windows), the growth of CO_2 concentration accompanies the increasing lack of oxygen (2 in Fig. 22). The carbon monoxide is quickly assimilated through hemoglobin (about 200 times quicker than oxygen). In a human organism it forms carboxyhaemoglobin (HCOb). In accordance to May´s investigations [16], 50% concentration of this compound in blood is able to kill a man. In majority of studied bathrooms the concentration of carboxyhaemoglobin (defined with the help of the May graph), crosses 40% in 5 to 7 minutes' time (3 in Fig. 22). It creates extremely risky conditions, confirmed by the practice.

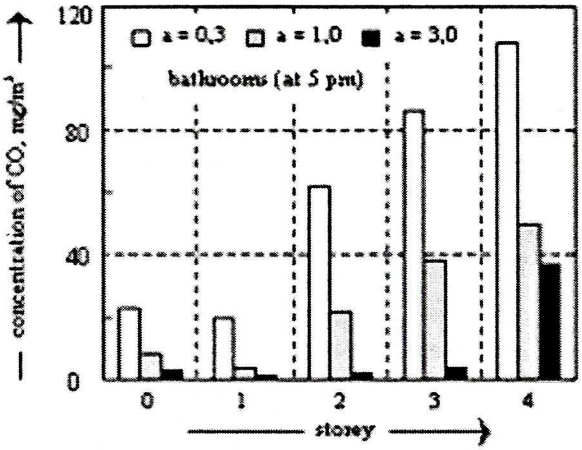

Fig. 21. Dependence of CO concentration on airtightness of windows in 4 storeyed building in winter season (air coefficients are expressed in m³/mh for 1 daPa)

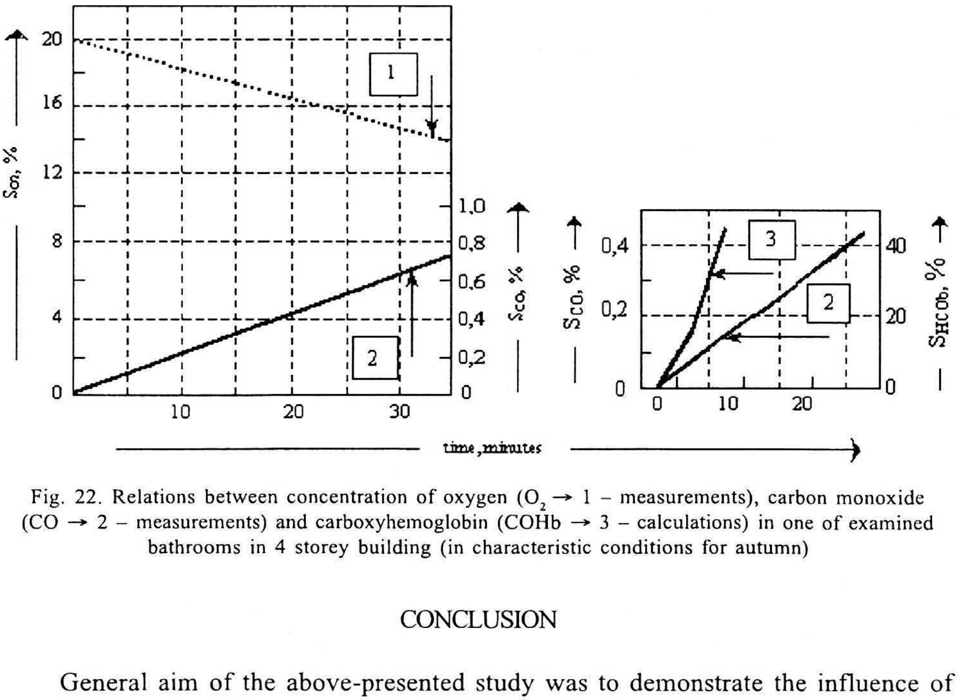

Fig. 22. Relations between concentration of oxygen (O_2 → 1 – measurements), carbon monoxide (CO → 2 – measurements) and carboxyhemoglobin (COHb → 3 – calculations) in one of examined bathrooms in 4 storey building (in characteristic conditions for autumn)

CONCLUSION

General aim of the above-presented study was to demonstrate the influence of ventilation on selected indoor parameters of naturally ventilated buildings, the impact of airtightness on ventilation rate and concentration of some pollutants. Findings of the presented study can be summarized as follows:

1. The state of indoor air is the function not only of the presence of polluting sources but also of air change rates. Among serious short-time health effects such as headaches, dizziness and other symptoms were listed. They were attributed to higher concentration of indoor contaminants.

2. In many practical cases, natural ventilation rate depends on airtightness of external walls, especially windows. If ventilation rates are limited by standard airtightness, the CO_2 concentration can be higher than 3000 ppm.
3. Ventilation rate in heating season is the determining factor for indoor air quality. If ventilation rates are limited by high airtightness of windows, the concentration of various and dangerous pollutants is higher.
4. As far as concentration of CO_2 or other pollutants is concerned the results showed that intensity of indoor air motion is a critical factor in all tested buildings, especially in blocks of flats.
5. Main danger of buildings equipped with home gas devices to prepare warm water and make meals, is the periodical raise of partial combustions products (mainly CO) and its migration in rooms and buildings.

Natural ventilation is a sustainable and energy-efficient technology that is well-accepted by occupants, but the correct design of natural systems is difficult. In a mild climate (like in Poland), air flows supplied by natural ventilation are insufficient for good air quality. Therefore, the recent way of determining air flows organization, especially defining the airtightness of windows must be changed.

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