INDOOR CLIMATE AND ENERGY CONSUMPTION IN BUILDINGS WITH NATURAL VENTILATION

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Abstract

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 designs of new buildings and the retrofit of existing buildings, traditional structure of natural ventilation is used. In these cases, the ventilation is an important tool for a desirable realization of all environmental and energy requirements. The paper presents selected results of long-term research work. These results were obtained by questionnaires, measurements and simulations of ventilation and heating 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 and energy consumption. In conclusion, ways of airtightness, ventilation and heating strategies are presented.

Streszczenie

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.

Keywords: **natural ventilation; airtightness; indoor air quality; energy consumption.**

1. INTRODUCTION

Major function of buildings is to provide their users protection from outdoor climate and maintain acceptable indoor environment, i.e. thermal comfort and indoor air quality. To realize this aim, a building should fulfil minimal energy (heat) demands and should be equipped with proper heating and ventilation systems. Keeping in mind that buildings are major capital investment and man's health is invaluable, the prospect of high energy consumption and poor indoor environment prevailing inside them, does contradict before mentioned function of building. It is essential to obtain a comfortable indoor climate in the design of any heating and ventilating plant, what minimizes costs and operating problems [1,2,3]. We have become aware the importance of the indoor climate on human well-being and productivity. This has led to more severe requirements, encouraging manufacturers to develop new control equipment, including optimization functions, advanced control and supervision equipment. 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 control equipment cannot always achieve their theoretical assumptions. The reason for this is simple: ideal conditions that normally must be satisfied are not respected for them to operate correctly.

The ventilation rate is rarely decisive for heat demand, especially for new blocks of flats, and, in general, for their energy consumption. In a naturally-ventilated building, air enters either due to uncontrolled infiltration or through purposely provided openings (like windows) due to the combined action of wind and air temperature differences between the inside and outside of a building (the stack effect). The process of ventilating in Polish buildings is often realized by a traditional structure of natural ventilation [4, 5]. Buildings are ventilated primarily through ventilation openings or leaks in a building shell and hardly ever by openable windows. In this case, the action of exhaust ventilation ducts is accidental. Earlier code requirements for an outside shell insulation have been dictated above all by hygiene and comfort. Thermal insulation requirements were enforced but there were no demands on building airtightness. In this case, the coefficient of airtightness for windows varied between 3 and 6 m^3/mh at 1 daPa, and the energy balance was dominated by the conductive and ventilation heat demands. The example of such balance for detached house is illustrated in Figure 1. As shown, the fraction of ventilation heat demands is about 17%. This fraction in block of flats was varying between 30 and 40%. That the air leakage value for windows is high to requirements for a building airtightness. These requirements have been introduced by new Polish Standard in the 1980s as the range of air flow coefficients for windows (a – between 0.5 and 1.0 m^3/mh at 1 daPa or 0.03÷0.06 dm^3/ms at 1 Pa). Thermomodernization programs (with excessive air tightening), while concerning energy conservation, have tendency to a continuous increase of window leakage values and strong decrease of ventilation rates [5, 6]. Buildings are not only basic consumption goods but also space where people spend considerable part of their lives. Therefore, can be observed consequences of indoor environment are very serious. To what an extent it happens for airtight buildings with natural ventilation and the obsolete structure of heating systems. During last two decades, decreased ventilation rates with increased airtightness resulted in continuous increase of health complaints from building occupants. Building tightness without proper ventilation the system of provided can cause the increase of health and safety problems occurrence. Higher moisture levels found in inadequately ventilated buildings create environment for moulds, dust mites, the CO_2 concentration and other causes of respiratory problems and allergies. Tighter buildings are also more likely to experience problems from back drafting and spillage of combustion products from naturally drafting furnaces, water heaters and other fireplaces [7, 8, 9]. All buildings need supplies of outdoor air, not only for the comfort and health of occupants and efficient operation of combustion appliances, but also for the control of condensation. The set of health symptoms associated with building is called *sick building syndrome* (SBS) and include nasal, ocular and general diseases. Despite the fact that the exact definition of the cause of SBS is rather difficult, a declare of different complaints can be treated as a good index of indoor climate, especially for indoor air quality.

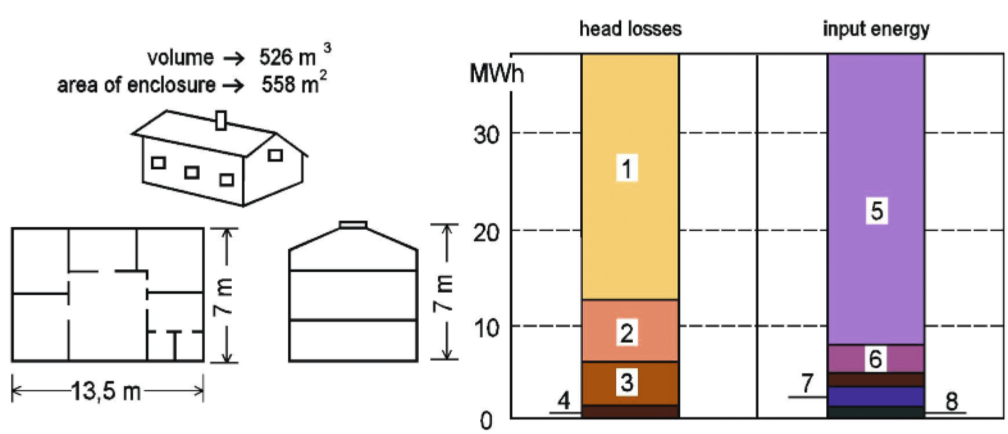

Figure 1.
Energy balance for one of detached houses. Notations: 1 – transmission losses, 2 – ventilation losses, 3 – waste water losses, 4 - domestic electricity, 5 – heating system, 6 – solar energy, 7 – hot water, 8 – internal heat gains

2. SURVEY AND METHODS OF INVESTIGATION

The survey was carried out between 1998 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. Examples of these buildings and their floor plan are shown in Figure 2 (the floor plan for detached houses is presented in Figure 1). The height of all blocks (BF) and office buildings (OB) is similar and equals 18 m (4 storey) and about 7 m for detached houses (DH – 1.5 storey). 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 volume is 0.62/m (for BF), 0.65/m (for OB) and 0.98/m (for DH). Blocks of flats and office buildings were located nearby the city area and built from hollow masonry units and prefabricated panels. The office buildings were not thermomodernized and their shells were 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).

These blocks of flats and detached houses are after modernization now and their shell is thermally insulated according to the new standards. The U-value for solid walls vary between 0.5 and 0.7 W/m^2K. In majority of the flats new and tight windows are applied (with wood or plastic frames). Similar values are in detached houses. The objects are equipped with 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 cellar of BF and OB or by the gas boiler in detached houses. All buildings are naturally ventilated with individual (1 in Figure 2) or collective ducts (2 in Figure 2). Blocks of flats and detached houses are equipped with gas stoves for preparing meals and boiling hot water (3 in Figure 2).

Occupants of the buildings were given two types of questionnaires to tell about their feelings while living in the buildings. The first one included questions about thermal comfort, ventilation system functioning in particular rooms and risk connected with the indoor emissions. The questions also concerned living conditions in flats, working in offices, the age of occupants, health and smoking habits, dust, odour, 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 indoor climate comfortable or uncomfortable?, etc. The second questionnaire was completed by professional auditors, upon their arrival to the building. It is based on European proposition presented in Finland NT-Report [10,11].

The quantity of heat in tested buildings was recorded by heat meters (Infocal 5) located near traditional

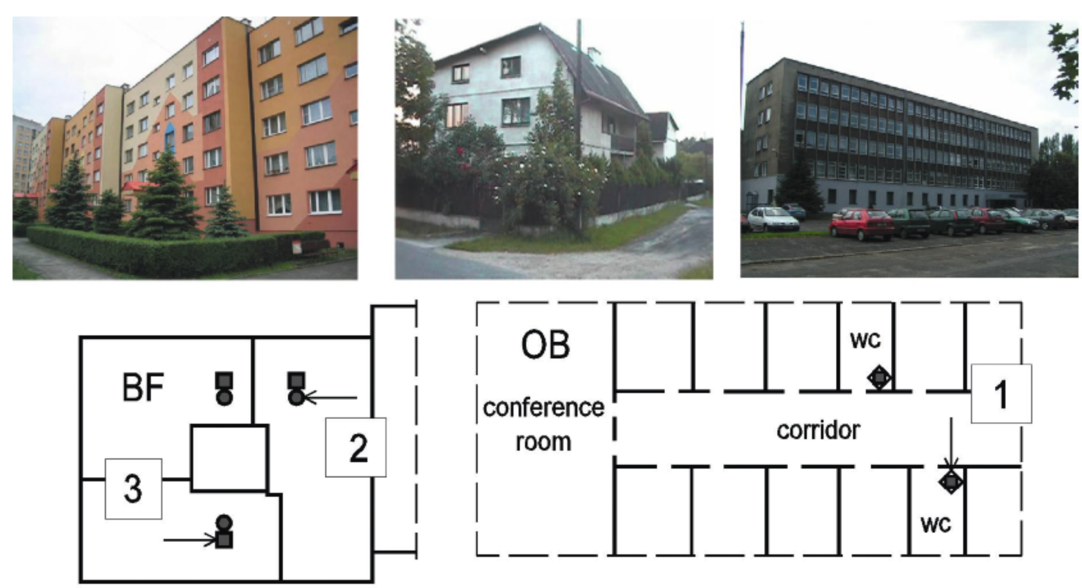

Figure 2.
View of tested buildings (from the left ③ block of flats - BF, detached houses – DH and office buildings – OB).
Notations: 1- individual ventilation ducts, 2 – collective ventilation ducts, 3 – gas pass ducts

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	Electrochemistry meter 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%)

sources of heat, i.e., boilers and heat engineering centres. Estimations of heat consumption was executed in chosen flats by heat meters located on every radiator. In order to evaluate the effects of ventilation, some research was done. 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 as well as the ventilation rate. This rate is also necessary to calculate the energy consumption. The instrumentation used in measurements is compared in Table 1.

To determine the air leakage values for windows and doors, pressurization tests were applied with the use of plastic cover tightly taped to the window and door frame. In this case test chambers were used (Figure 3).

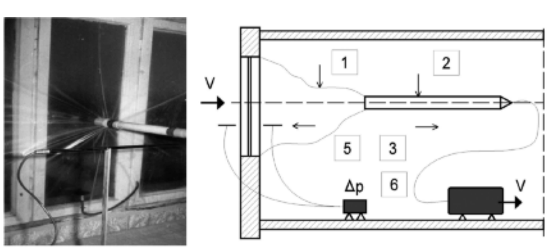

Figure 3.
Scheme of the experimental stand for determination of the leakage values (for windows). Notation: 1 – test chamber (in the photograph), 2 – duct, 3 – a hot-wire anemometer, 4 – fan, 5 – pressure difference, 6 – micromanometer

The fan inlet was connected to such chambers by a duct of about 1.5 m length and 0.2 m in diameter. The chamber was made of plywood panels covered in polyethylene sheets and was sealed with a tape around the perimeter of tested elements. Air flow rates of the fan were measured with an adjusted damper (accuracy of 10% of measured values). Pressure differences were measured with a diaphragm-type pressure transducer and digital voltmeter (static error about 5% of the scale). In selected rooms, flats and offices, large-scale pressurization tests were applied. Two types of stands were used (Figure 4). In the first case (the own stand – left side of Figure 4), 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 to the stand by the duct of 0.4 m in diameter. The entrance door was replaced by a plywood panel for tests. Tested spaces were pressurized, with the pressure differences from about 10 Pa to 100÷120 Pa at increments of about 10 Pa. The second type of test method was the pressurization or depressurization of space with a fan previously calibrated, made of plastic and fixed in a door (right side of Figure 4). The first and second method show pressure differences created by the fan between the inside and outside environment. If the airflow rate is induced by a fan (through space envelope), measured differences are expressed from the equation → $V = K(\Delta p)^{\alpha}$. So the tests must have been done for

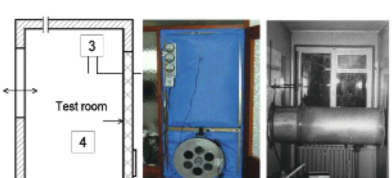

Figure 4.
The schematic diagram of large-scale pressurization test (for BF or OB). Notations: 1 – additional door with a duct (in the photograph), 2 – duct with a fan, 3 – pressure difference, 4 – blower door (in the photograph)

several Δp, 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. The accuracy of these tests is ±8%.

The ventilation rate for flats or particular rooms was also measured by using a gas technique with carbon dioxide as the tracer. Carbon dioxide was released by injection samples into the centre of tested space. Every 15/20 minutes after the tracer release, 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.

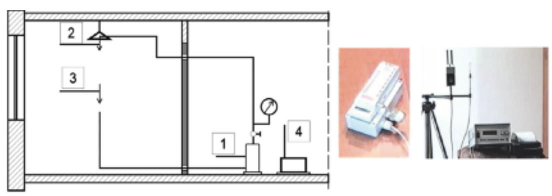

Figure 5.
Scheme of the measuring stand for gas technique. Notation: 1 – a gas tank, 2 – sample of gas inlet, 3 – sample of gas outlet (to the meter 4), 4 – meter of CO_2 concentration in indoor air – Air Tech 2006-SP (with data logger – in the photographs)

The average CO_2 concentration was about 5000 ppm (maximum 8500 ppm). This measurement lasted from 5 to 8 hours. Concentration changes were recorded and then ventilation rates were calculated. Accuracy of the measurement was about ± 2÷3%. 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 direction, etc.). Since measurements could only be made for a limited time they were therefore representative of only a small range of weather conditions. Various measurement data were used as input to numerical simulation so that a broader range of results for varying weather conditions could be established. Therefore, in the next stage of investigation air changes in buildings were calculated. Two types of methods were used. The first method was a sample analytical model of building [12]. The second method was a multi-zone model (network method). These analyses were accomplished with help of author's programme such as a *Symvent* [13]. The next step was detailed simulation of air flows and concentration of carbon monoxide and carbon dioxide in rooms or flats. These analyses were obtained with the help of the NIST code *Contam* [14]. Thermal balance of building can be carried by using the simulation code *Trnsys*. In this programme, the air exchange rate is declared as constant value for individual zones. In order to determine the real change of air it is convenient to use the numerical programme simulating air flows in the tested buildings. To achieve the change of natural air flows, the numerical programme *Contam* was used.

3. RESULTS AND DISCUSSION

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 6). The range of air temperature and relative humidity in winter season is presented in Figure 7. On average 17 to 58% (in flats) and 32 to 47% (in offices) of the occupants complained about hot or cold indoor air.

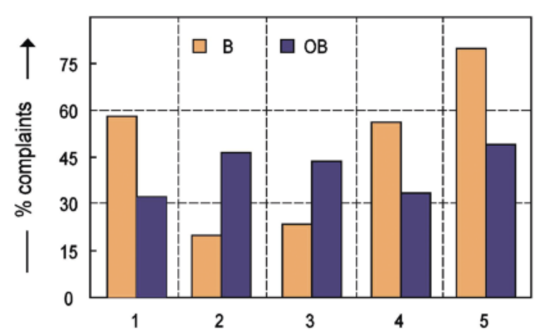

Figure 6.
Complaints concerning selected parameters (B = BF +DH). Notations: 1 – hot, 2 – cold, 3 – dry air, 4 – wet air, 5 – bad ventilation (lack of fresh-outdoor air)

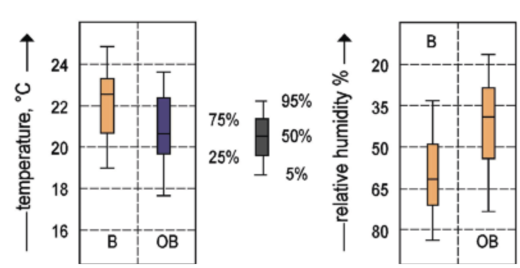

Figure 7.
Air temperatures and relative humidities in tested buildings (B = BF + DH)

The percentage of occupants complaining about relative humidity is 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%). Health symptoms reported by the employees in examined buildings are compared in Table 2. 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. Using gas devices caused strong nauseas, leading to frequent occurrence of vomiting. On average, occurrence of above mentioned symptoms per person was slightly higher in blocks of flats than in detached houses and office buildings.

3.1. Results of Measurements

Results of small-scale pressurization tests for windows and main entry doors are presented on Figure 8. On average, the air coefficient for all windows is about 0.06 dm^3/ms at 1 Pa and for door – 0.12 dm^3/ms at 1 Pa (1 m^3/mh at 1 daPa and 2 m^3/mh at 1 daPa). For windows these values are compatible to with Polish requirements.

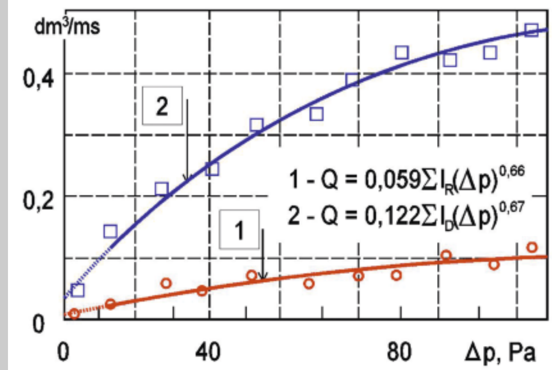

Figure 8.
Representative results of a small-scale pressurization tests for windows (1) and doors (2)

Table 2.
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%)

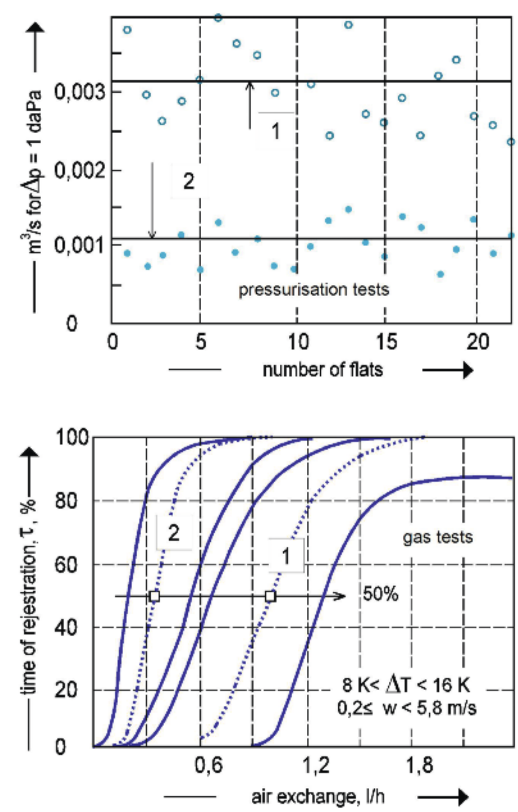

Figure 9.
Results of pressurization and gas tests in one of tested blocks of flats. Notations: 1 – before thermomodernization, 2 – after thermomodernization

Table 3.
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

The most representative for evaluation of room tightness were large pressurization tests, and particularly – gas techniques. Example results of such investigations are presented in Figure 9. These results related to 22 flats located in one of tested blocks. On average, the airtightness of external walls after modernization was about three times higher than before it (0.0032 → 0.0012 m^3/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 rooms can be increased when windows are partly open. If the windows are partly open, the air exchange increases to 0.6÷0.8/h (open in about 15%) and even to 1.6÷2.7/h (open in 30%). On the basis of gas tests, the ventilation rate in a flat was also determined. This rate is about 0.2/h. The average air change rate for detached houses is similar (from 0.15/h to 0.25/h). The influence of ventilation on concentration of selected contaminants (dioxide nitrogen, formaldehyde, ozone, etc.) was measured in all buildings. Mean indoor/outdoor ratios (I/Q) estimated for different rooms are always above 1, especially for HCOH and CO (Table 3).

When the rooms were unoccupied, the indoor/outdoor ratios were a little higher than 1 (probably because of the absence of majority of indoor disturbances). When the rooms were unoccupied, the indoor/outdoor ratios were a little higher than 1 (probably because of the absence of majority of indoor factors). For example, when people were in rooms, this ratio for formaldehyde varied between 5 and 16.

Carbon dioxide is used here as indicator of the air quality, and the critical threshold when the air is still of acceptable quality should be lower than 1000 ppm. In accordance with the relationship between inhabitants perception of indoor air quality and concentration of the CO_2 (percentage of dissatisfied – ppd), 20% ppd corresponds to the concentration of 650 ppm. 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 is 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 is usually assumed. Figure 10 presents CO_2 concentration in one of the tested offices. As shown, average CO_2 concentration per hour varies between 410 ppm when the office is 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 11 are representative for rooms located in blocks of flats. In this case, the concentration of CO_2 varies also between 600 ppm and about 3000 ppm (or higher).

In chosen flats of BF equipped with typical home gas devices, the measurements of CO concentration were also conducted. The largest CO concentrations were noted in kitchens and, especially, in bathrooms (without windows). In bathrooms located on central and upper parts of buildings, CO concentration after about 10 minutes of exploitation of gas heaters hesitated among 20 to 25 mg/m^3. For kitchens in the same conditions, the amount of CO concentration was considerably smaller and varied between 4 and 8 mg/m^3.

The average fraction of main ways of total energy consumed for tested group of buildings is presented in Figure 12. As shown in this figure energy consumption in all buildings is still dominated by the heat transmission. This domination is greatest in detached houses. Ventilation rate in blocks of flats and detached houses are very small in comparison to requirements in office buildings.

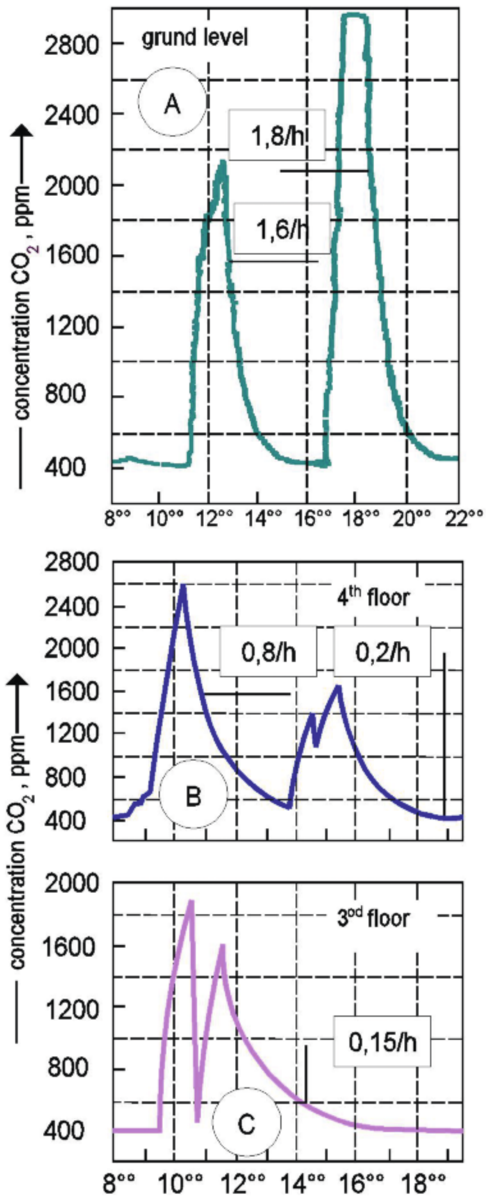

Figure 10.
CO_2 concentration in three offices. Notations: A – the old windows and smoking, B – the tight windows and smoking, A,B – smoking (often), C – with tight windows

It is the effect of airtightness of windows and reduced ventilation rates to about 0.1÷0.2/h.

3.2. Results of Simulations

Some results of investigation for flat and rooms located on a ground floor of blocks are presented in Figure 13. Assumed air leakage coefficients for all windows are about 1 m^3/mh at 1 daPa and for doors – 2 m^3/mh at 1 daPa (according to the rules of Polish

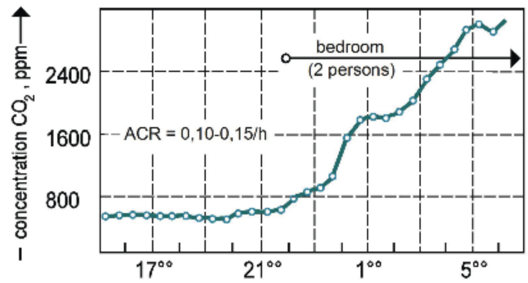

Figure 11.
CO_2 concentration in bedroom with tight windows located on the 2nd floor level (t_e≅0°C, w≅0.3m/s)

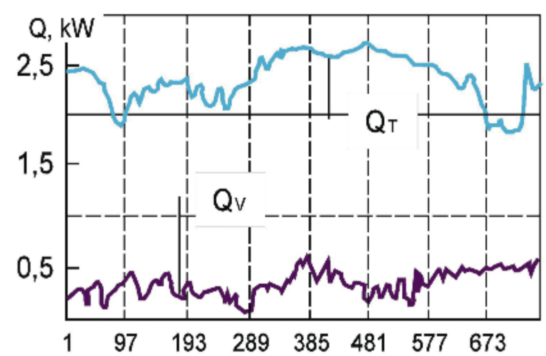

Figure 12.
Comparison of an hourly total heat consumption (Q_T) and heat consumption on ventilation (Q_V) for flat (volume 167 m^3) located on ground level of one of tested buildings (example for February)

Standards and to results of measurements). Natural (gravitational) ventilation with individual ducts to each flat (0.14×0.14 m) is used in the tested buildings. 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), were established according to the lifestyles of residents, as the results of questionnaires showed [11]. Meteorological data used in simulation was based on real climate parameters with 1-hour time-step for heating season in Katowice.

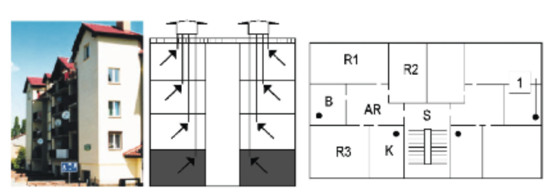

Figure 13.
View and internal layout with selected section of simulated building. Notations: R1,2,3 – rooms, B – bathroom, K – kitchen, AR – anteroom, S – stairway, 1 – ventilation ducts

The first group of simulation results includes these referring to air exchange of the whole flat. Figure 14 shows time-variables of air flow into flats located on the ground floor and on 3rd floor. The average values of air change rates for January give about 0.13/h (for a flat located on 3rd floor) and 0.42/h (for a flat located on the ground floor). These values are lower than the standard value (1/h).

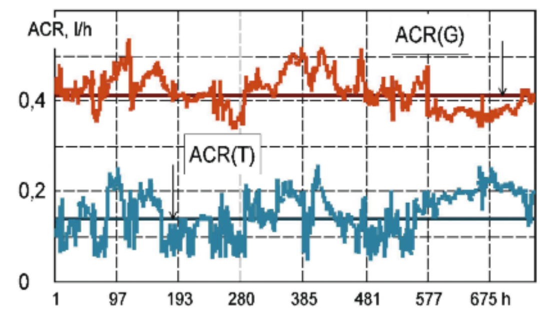

Figure 14.
Run of ventilation rate in chosen flats of the building (the air leakage coefficients for windows are 0.06 dm³/m×s at 1 Pa). Notations: ACR(G) and ACR(T) – the air change in the flat located on the ground and the top storey

The changeability of air flows through selected rooms in a flat located on the ground floor of tested blocks are presented in Figure 15. This picture is characteristic for majority of buildings with natural ventilation. Typical abnormalities in tested cases are backflows in one of the ducts (VOK in Figure 15). In other flats the picture of air flows is more unfavourable. Air flows in these flats and rooms correspond with the lack of air exchange rate. In the best case, the personal ventilation rate varies between 0.58 dm^3/s (for room R1 and 1.15 dm^3/s (for room R3) and is lower than required value (about 5.5 dm^3/s). The concentration of carbon dioxide in this situation are very high. Average concentration in tested rooms varied between 3000 ppm and 5000 ppm (Figure 16). It is the effect of excessively tight windows.

Main danger in flats equipped with home gas devices is a periodical rise of concentration of partial gas combustion products. Some results of simulations made for 4-storey block of flats equipped with ventilation ducts providing natural ventilation, gas passes and typical gas cookers (in kitchens) and water heaters (in bathrooms) were obtained with help the Contam programme. The following temporary profiles of the 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. The variable airtightness of building woodwork was also considered (from 0.3 to 3 m^3/mh at 1daPa – ventilation openings in windows were not applied). A year-period of changes of external parameters climate were recorded every hour: the temperatures, velocity

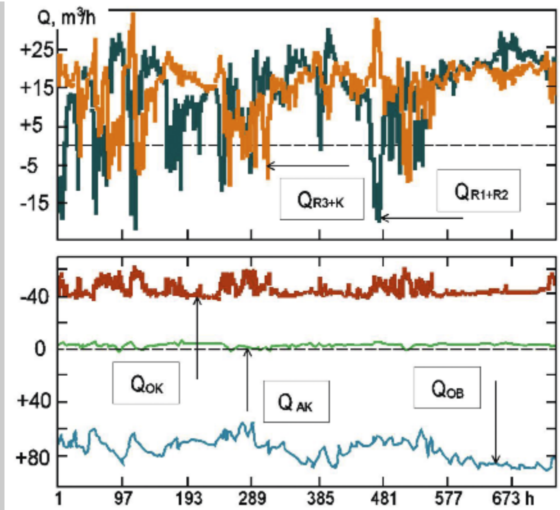

Figure 15.
Hourly run variation of air flows in the flat located on the ground level of simulated building (the air leakage coefficients for all windows are 0.06 dm³/m×s at 1 Pa). Notations: Q_{R1+R2}, Q_{R3+K} – air inlets through gaps in windows, Q_{AR} – as above but through gaps in the door (from the stairway), Q_O – air outlets by natural ducts (from the kitchen – Q_{OK} and bathroom – Q_{OB})

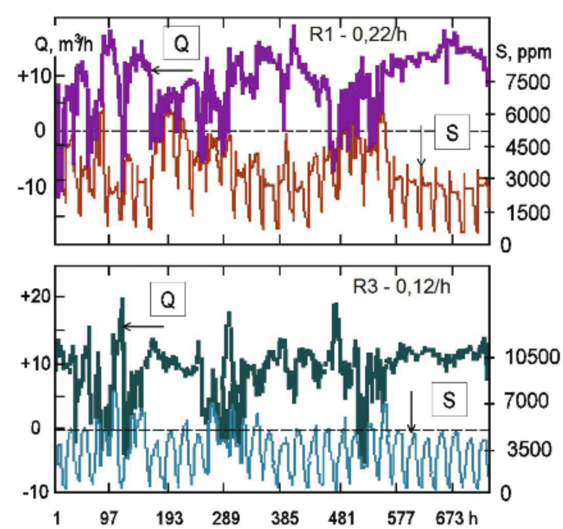

Figure 16.
Changeability of air flows (Q) and CO_2 concentration (S) for two rooms (R1 and R3 as in Figure 20) and the leakage coefficients for all windows → 0.06 dm³/m×s at 1 Pa

and directions of wind as well as concentrations CO and NO_2 in outdoor air. Computations were made to estimate combustion products mentioned previously and their migration inside considered buildings. Data presented in Figure 17 describe concentration of these pollutants for kitchens and bathrooms located in one of vertical sections of a building. In bathrooms values of these concentrations are several times higher than in kitchens.

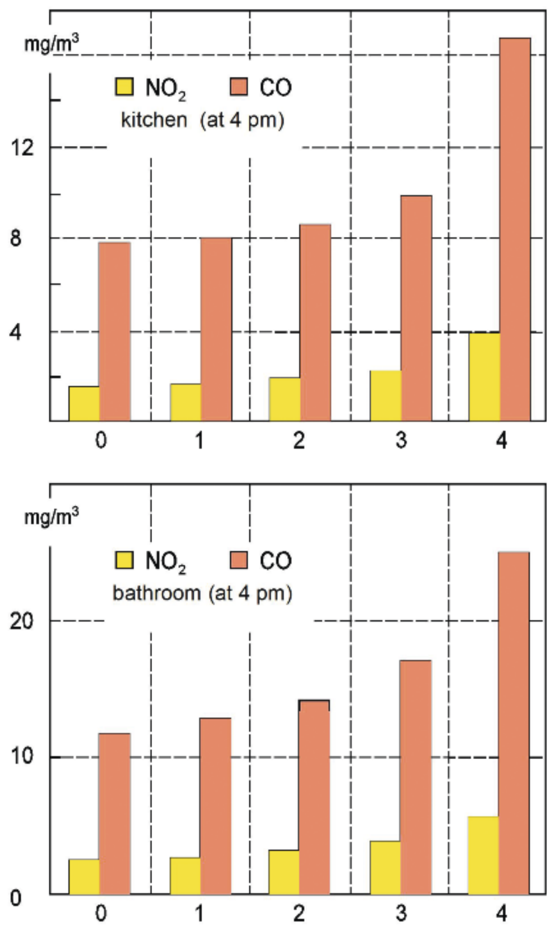

Figure 17.
Concentration of NO_2 and CO inside kitchens and bathrooms located in several storeys and equipped with airtight windows (21 January) the air leakage coefficients for windows are 0.02 dm³/m×s at 1 Pa or 0.3 m³/m×h at 1 daPa

The increase of pollution concentrations inside these rooms depending on height of the building can be observed. Such changes also appear for changing the weather conditions and depend on window tightness. Data presented in Figure 18 confirm this assumption. Because of 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.

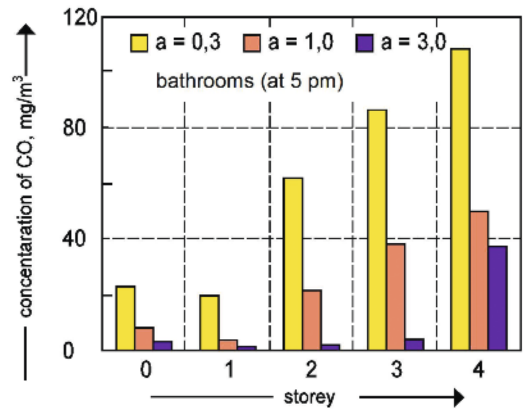

Figure 18.
Dependence of carbon oxide concentration and air tightness building windows (the air leakage coefficients for windows a = 0.3; 1.0 and 3.0 m³/m×h at 1 daPa)

High tightness of windows resulted in the raise of pollution concentration. But it does not always appear. For example, the maximal CO concentration can accompany medium value of airtightness (i.e. 1 m³/mh at 1 daPa) in flats located on the highest storey. 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 a dangerous raise of pollution factors usually happens in transient periods with high velocity winds and their variable direction (spring, autumn). Time periods of these uncomfortable conditions lengthen considerably in the case of building located in valleys and hills or areas of compact building development, e.g. town centres. It is obvious from presented results that dangerous conditions for people living or working in considered buildings last for 150 or even 200 hours a year. It means that there is high risk of health hazard for about 75% of one year's time for people living in these buildings. Obtained results can be used for prediction of dangerous situation 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 Figure 19). The carbon monoxide is quickly assimilated through haemoglobin (about 200 times quicker than oxygen).

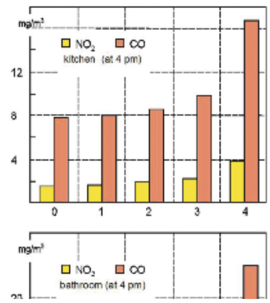

Figure 19.
Relations between the O_2 (1), CO_2 (2) and HCOb concentration (3) in one of tested bathroom (located on 2nd floor in 4 storey building)

In a human organism it forms carboxyhaemoglobin (HCOb). In accordance to May's investigations [8], 50% concentration of this compound in blood is able to kill a man. In the majority of tested bathrooms the concentration of HCOb (defined with the help of May graph), equals 40% in 5 to 7 minutes' time (3 in Figure 19). It creates extremely risky conditions, confirmed by the practice [9,11,15].

Energy consumption in buildings also depends on electrical energy of lighting, computers, etc. Chosen results of energy consumption predictions are illustrated in Figure 20. It can be easily noted that real ventilation is responsible for a small amount of total heat losses. In the result of similar calculation made for requirements of the air exchange rate (about 1/h), the heat consumption for ventilation increases to 55÷65%. These proportions for the office buildings are different. In these buildings the ventilation was accounted for 26÷44% of their total heat losses. The specific energy consumption in office buildings varies between 135 and 150 kW/m^{2}a and for dwelling houses equals about 95 kW/m^{2}a.

4. CONCLUSION

The general aim of above presented study was to demonstrate the impact of ventilation on:

- the selected indoor parameters and the energy consumption of a naturally ventilated buildings,
- the impact of airtightness on the ventilation rate,
- concentration of metabolically produced carbon dioxide in a flat.

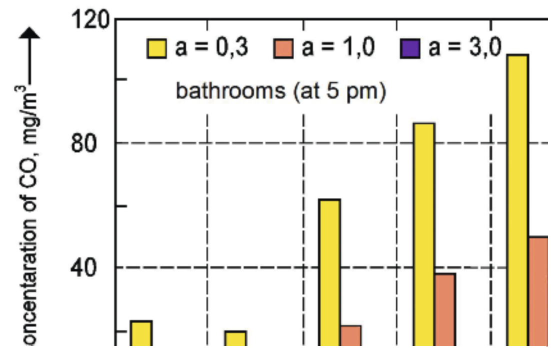

Figure 20.
Division of total energy consumption in tested buildings. References: 1 - transmittance losses, 2 – ventilation heat losses, 3 – hot water consumption, 4 – electrical energy

The findings of the all presented study can be summarized as follows:

- In many practical cases, the natural ventilation rate depends on airtightness of external walls, especially on windows. If the ventilation rates are limited only by standard airtightness of windows, the CO_2 concentration can be higher than 3000 ppm.
- The ventilation rate in heating season is the determining factor for indoor conditions, especially for indoor air quality; if the ventilation rates are limited by high airtightness of windows, various pollutants concentration is higher.
- The parameters of indoor environment not only depend on indoor pollutants, but also on the air exchange. The influence of these pollutants on human health is known only for short periods of time.
- The results indicated that ventilation does play an important role in indoor air quality; as far as CO_2 or other pollutants concentration are concerned, the results showed that intensity of indoor motion is a critical factor in all of tested buildings, especially in blocks of flats.
- Main danger inside buildings equipped with home gas devices is the periodical rise of concentration of partial gas combustion products (mainly CO) and

its free migration inside buildings.

- Analyses show that lowering of water temperature in heating systems (especially in indoor installations) can provide decrease of energy consumption for systems with renewable heat sources.

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