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Optimisation of Heat Loss through Ventilation for Residential Buildings

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Abstract: This study presents the results of research on heat loss from various types of residential buildings through ventilation systems. Experimental research was done to analyse the effectiveness of ventilation systems of different types and determine the parameters of air discharged via the ventilation ducts. A model of heat loss from the discharge of exhaust air outside through air ducts has since been developed. Experiments were conducted on three experimental systems of building ventilation: gravitational, mechanical, and supply-exhaust ventilation systems with heat recovery. The proposed model dependencies were used to chart the daily fluctuations of the optimum multiplicity of air exchange for precise control of the parameters of mechanical ventilation systems in residential buildings. This study proves that natural ventilation in residential buildings fulfils its function only by increasing the air flow into the building, and that this incurs significant heat loss from buildings during the heating season.

Keywords: heat loss; optimisation; residential building; air quality; carbon dioxide concentration; ventilation system

1. Introduction

In the context of the debate on climate change and the need to increase the energy efficiency of buildings, viable means of reducing heat loss from the ventilation of residential buildings that have to be heated must be found. In some climate zones, the use of natural ventilation brings the expected effects [1,2]. However, in the climatic conditions throughout Poland, as well as most other countries of Central and Northern Europe, this ventilation system does not guarantee high energy efficiency. About 80% of single-family and multi-family low-rise residential buildings (up to four stories) in Poland have natural ventilation (Polish standards do not permit natural ventilation in multi-family high-rise buildings). It is therefore necessary to undertake research to determine the performance of the different types of ventilation systems used in residential buildings in Central and Northern Europe to reduce energy loss through ventilation systems.

Ensuring comfort in residential buildings requires selecting the right air parameters, i.e., temperature, humidity, and concentration of gas, particulate pollutants, and microorganisms. These factors significantly affect the well-being and health of people living in such spaces [3–5]. Failure to provide adequate air quality causes residents to experience a number of symptoms of sick building syndrome (SBS) [6,7] including headache, dizziness, dry linings, drowsiness, shortness of breath, and fainting.

It should be noted, however, that the effects of exposure of a human being to a harmful substance are assessed by its dose, and not the concentration or distribution. Reducing residents' exposure to harmful substances requires reducing the concentration of harmful substances or the time they spend in a polluted room. Shortening their time in living spaces is not generally feasible (e.g., at night): the only solution is to reduce the concentrations of pollutants. This can be achieved by reducing emissions or by bringing in more fresh air to dilute pollutants, and this can be achieved by a ventilation system [8,9].

Ventilation of a residential space is the exchange of air throughout the whole space or parts of it in order to remove the used, contaminated air and introduce fresh air from outside. In other words, ventilation is an organised exchange of air in a given space in order to refresh it and drive the contaminants which are produced in that space outside [10–12].

The concept of indoor air distribution must be developed in such a way as to obtain the required ventilation effects. The efficiency of the ventilation system should be defined via measurable flow parameters, such as the local distributions of air velocity and temperature, concentrations of pollutants, etc. In the zone where people are continually present, the analysis of air parameters allows specification of the optimum distribution of indoor air and achievement of the most favourable parameters [13,14].

It should also be emphasised that the ventilation air stream, when properly adjusted for living spaces, can reduce the pollution of suspended particles emitted by internal sources, e.g., household appliances, computer printers, cigarettes, or electronic cigarettes. This contributes significantly to the comfort of people in rooms where high air quality is maintained [15–18].

In Poland, the regulations concerning ventilation air streams and the performance of ventilation systems are specified in the Polish Standards and the following legal acts:

- The Act of 7 July 1994, Construction Law (as amended) [19];
- Regulation of the Minister of Infrastructure of 10 December 2010, on the technical requirements for buildings and their locations [20];
- Polish Standards:
    - PN-B-03421:1978 "Ventilation and air conditioning—parameters for indoor air in the habitats designated for permanent presence of people" [21],
    - PN-B-03430:1983/Az3:2000 "Ventilation in residential, common living, and public buildings—requirements" [22],
    - PN-EN 13779:2007 "Ventilation for non-residential buildings—performance requirements for ventilation and room-conditioning systems" [23].

This work does not refer to European standards or standards in other countries of Central and Northern Europe, and the requirements set out in the above regulations vary significantly. The research was carried out in facilities located in Poland, so only Polish regulation is referenced. Unfortunately, Polish regulation does not always align with European Union regulation.

Meeting the requirements set forth in the above regulations does not ensure appropriate levels of air pollutants in buildings. The air that enters the building through the ventilation system is, in ventilation terminology, called fresh air, and it of course does not always meet the quality parameters required of the air in living spaces. External air in city centres can carry both exhaust and dust pollution [24], and substantial flows of external air into a building can reduce the air pollution in ventilated spaces only slightly or in extreme situations actually increase it. In most ventilation systems, fresh air is supplied by infiltration, i.e., the spontaneous flow of air through the leaks in doors, windows, and walls.

Standard PN-EN 13779:2007 [23] indicates three classes of outside air based on purity (as presented in Table 1).

Table 1. Outside air classification based on PN-EN 13779 [23].

Category	Description
ODA 1 (ZEW 1)	Clean air, which can be dusty only periodically (e.g., with pollen—in accordance with the WHO 1999 recommendations)
ODA 2 (ZEW 2)	Outside air with high-level concentration of pollutants: particulates and gas
ODA 3 (ZEW 3)	Outside air with high-level concentration of pollutants: particulates and gas (WHO standards exceeded more than 1.5 times)

The classification of the outdoor air according to the categories listed in the Polish Standard PN-EN 13779:2007 is not, however, precise enough for use in the optimisation of ventilation systems in residential spaces. Therefore, studies and analyses of outdoor air were carried out at measuring points in the provinces of Silesia, Opole, and Lower Silesia. The research was conducted by the author during field studies, which involved university students, in areas where buildings selected as research objects in this paper were located. This made it possible to determine the parameters of outside air supplied to the building by the ventilation systems in different climatic conditions. The author recorded the average concentrations of pollutants in the outdoor air at measuring stations located in areas of varying character throughout the region of analysis in Poland, and the figures are shown in Table 2.

Table 2. Sample average concentrations of pollutants in outdoor air.

Measuring Stations	Concentrations of Pollutants					
	CO_2	CO	SO_2	NO_2	PM_{10}	Total Suspended Particulates
	(ppm)	$(mg\cdot m^{-3})$	$(\mu g\cdot m^{-3})$	$(\mu g\cdot m^{-3})$	$(\mu g\cdot m^{-3})$	$(mg\cdot m^{-3})$
Rural areas with low population density	320	1	4	5–35	do 15	0.5
Small towns with no large production plants	390	1.5–4.0	6–14	15–40	20–40	0.5–1.0
Central districts of large urban developments or cities with production plants	580	3.5–8.0	20–60	30–80	30–70	1.0–2.0

As can be inferred from the data summarised in Tables 1 and 2, large streams of fresh air do not always ensure good air quality in living spaces. On the other hand, excessive ventilation of living spaces during the heating season causes greater heat loss in the building as the ventilation system sends heated air outside [25,26]. Substantial heat losses by ventilation systems translate directly into higher costs of heating of the building, and ways should be found to reduce them.

An initiative was undertaken to create a model for optimisation of the performance of the ventilation system in a building that would ensure the required indoor air parameters recommended by Polish Standards, as well as by WHO (concentration of CO_2 below 1000 ppm) [27], with minimal building heat loss.

2. Experiments

As confirmed by the analyses carried out by a number of authors [11,28–31], 30 to 40% of the heat loss from residential buildings in various climatic conditions is discharged into the atmosphere together with the used air via the natural ventilation systems. In order to optimise the performance parameters of the ventilation system and simultaneously minimise heat losses via ventilation in a residential building, it is necessary to determine the unit heat flow driven out of the building together with the used air over one hour. Unit heat flow can be determined by Equation (1):

$$\dot{Q}_w = \frac{1}{3600} \cdot \dot{V} \cdot \rho \cdot c_p \cdot (T_w - T_o) \tag{1}$$

where $\dot{Q}_w$ is the heat loss-unit heat flow driven out of the building together with the used air $(W\cdot h^{-1})$; $\dot{V}$ is the ventilation airflow $(m^3\cdot h^{-1})$; ρ is the air density $(kg\cdot m^{-3})$; c_p is the specific heat of the air at constant pressure $(J\cdot(kg\cdot K)^{-1})$; T_w is the indoor air temperature (K); and T_o is the temperature of fresh outside air (K).

In Equation (1), the air temperature inside the building, T_w, is a constant. In the heating season, it is 293 K (20 °C); out of the heating season, it is 296 K (23 °C). Therefore, it can be assumed that the values of density ρ and specific heat c_p of the air are also constant. The outside temperature value is read from the climate databases (measured during field tests at the specific location of the building, the average temperature values are given for the selected months). In the case of natural ventilation, where fresh air is supplied into the building from outside in an uncontrolled manner (via leaks in construction elements), no changes in temperature are possible. Raising the temperature of fresh air is possible for mechanical ventilation with heat recovery by means of a recuperator or a ground heat exchanger. To a large extent, however, it is possible to control the value of the ventilation airflow $\dot{V}$. Carbon dioxide concentration is one of the important indicators of indoor air quality. Particulate pollutants were not taken into account during the analysis because they are nearly completely eliminated by the inlet filters regardless of whether air is taken in by mechanical ventilation or natural ventilation. Therefore, when defining the minimum ventilation airflow, carbon dioxide concentration and the relative humidity of the air are the primary indicators of air pollution inside a living space [32]. Air humidity affects only the flow of ventilation air being removed from bathrooms or kitchens. For the total living space, it is sufficient to correlate the flow of ventilation air with the concentration of carbon dioxide. Therefore, Equation model (2) (based on the established balance sheet equations, extended by empirical factors determined in the course of this analysis) was selected for determining the optimum ventilation flow for residential buildings and living spaces:

$$\dot{V} = \alpha \cdot \frac{\varepsilon_M}{C_D - C_Z} \cdot V_B \tag{2}$$

where α is the correction coefficient of the standard ventilation rate (no unit); ε_M is the indoor carbon dioxide emissions from human sources (ppm$\cdot$h^{-1}); C_D is the permissible level of carbon dioxide in indoor air in residential buildings (ppm); C_Z is the concentration of carbon dioxide in the outdoor air (ppm); and V_B is the volume of heated space in the building (m^3).

The correction coefficient of the standard ventilation rate, α, is an empirical coefficient that takes into account the number of people in the facility and their activities, as well as other sources of carbon dioxide, e.g., a gas stove or a fireplace. The database of the values of α, which is necessary for optimisation calculations, covering most of the circumstances occurring in residential premises and buildings, was prepared on the basis of long-term studies of ventilation systems in residential buildings, having analysed the correlation between the number and activity of the residents and the concentration of carbon dioxide.

The values of the carbon dioxide emission coefficient for individuals with different physical characteristics and their activity profiles were determined by the author during metabolic tests. Metabolic tests were carried out in apartment 2 and they involved recording changes in the concentration of carbon dioxide in the selected room (with a specific cubic capacity) used by one person. In that room air exchange was stopped, and in a subsequent series of tests selected individuals performed different activities (e.g., 4 h of sleep, computer work, or simple physical exercises).

In the case of mechanical ventilation with heat recovery by means of a recuperator or ground heat exchanger, the temperature of the fresh air entering the building through the ventilation system needs to be specified. Therefore, Equation (3) is proposed to specify the temperature of the fresh air entering the building, T_o:

$$T_o = T_Z +_R [T_W - T_Z +_G (T_Z + T_G)] \tag{3}$$

where T_Z is the outdoor air temperature (K); T_G is the ground temperature in the ground heat exchanger (K); η_R is the recuperator heat recovery efficiency (no unit); and η_G is the thermal efficiency of ground heat exchanger (no unit).

The modified classical balance Equations (1)–(3), the climate database for southwestern Poland, and the empirical factors determined on the basis of the conducted studies and analyses resulted in a model for selecting optimal performance parameters for a residential building ventilation system. In order to verify the proposed model dependencies and analyse the effectiveness of ventilation systems, as well as to specify the parameters of the exhaust air driven outside via the ventilation ducts, experimental research was conducted and theoretical calculations were made for seven ventilation systems in residential buildings and apartments equipped with various ventilation systems. The following objects of study were selected:

- three apartments:
    - Apartment 1 with a floorspace of 48 m^2 and mechanical exhaust ventilation;
    - Apartment 2 with a floorspace of 37 m^2 and natural ventilation;
    - Apartment 3 with a floorspace of 69 m^2 and natural ventilation, after an energy efficient upgrade involving the improvement of the building insulation and replacement of window joinery for better air tightness;
- four single-family/detached houses:
    - House 1 with a floorspace of 170 m^2 and natural ventilation;
    - House 2 with a floorspace of 117 m^2 and natural ventilation, after an energy efficient upgrade;
    - House 3 with a floorspace of 158 m^2 and mechanical ventilation—intake and exhaust with heat recovery;
    - House 4 with a floorspace of 204 m^2 and mechanical ventilation—intake and exhaust with heat recovery and ground exchanger;

In order to compare the results of the research for individual research objects, residential apartments inhabited by three people were selected, and single-family buildings were selected with four inhabitants.

The research objects were selected specifically because they have ventilation systems of the three types of air flow distribution, presented graphically in Figure 1.

The tests were carried out in the selected research objects from October to April, i.e., in the period when the rooms were heated. Measurements were carried out in five-day cycles, 24 h a day, recording the measured air parameters every 5 min at selected points in the tested objects. The tests were conducted only on weekdays, when the daily cycles of residents' activity were nearly identical. This approach allowed for a comparison of the results of tests conducted in different objects and in different weather conditions. All windows in the research objects were closed at all times. The fresh air was introduced into the spaces only through micro ventilation openings and wall diffusers. According to research conducted by numerous authors, ventilation by opening windows in buildings with natural ventilation can reduce the CO_2 concentration but can simultaneously increase dust pollution and heat demand for the building [33].

Measurements of the concentration of carbon dioxide, relative humidity, and air temperature were taken in kitchens, bathrooms, and other rooms in the objects; an average value for each entire object was then determined. Air streams in individual ventilation ducts were calculated on the basis of the velocity of air flow at various points of entry into the ventilation ducts. The velocity was measured by a Kestrel 2000 anemometer, which allows for measurement definition up to 0.1 m/s and measuring accuracy of ±3%. Measurements of the air pressure, temperature, and relative humidity were taken by a Commeter C4130 thermo-hygro-barometer. It recorded temperature to an accuracy of 0.4 °C, relative humidity within ±2.5%, and atmospheric pressure within ±2 hPa. Carbon dioxide concentration measurements were taken using the multifunction carbon dioxide meter AZ 77535, accurate to 10 ppm ±5% of the reading. Tests were only carried out on weekdays, when the daily activity cycles of the inhabitants were nearly identical. The same procedure was applied for all tested objects. This approach made it possible to compare the results of tests carried out at different times of the year and in different weather conditions.

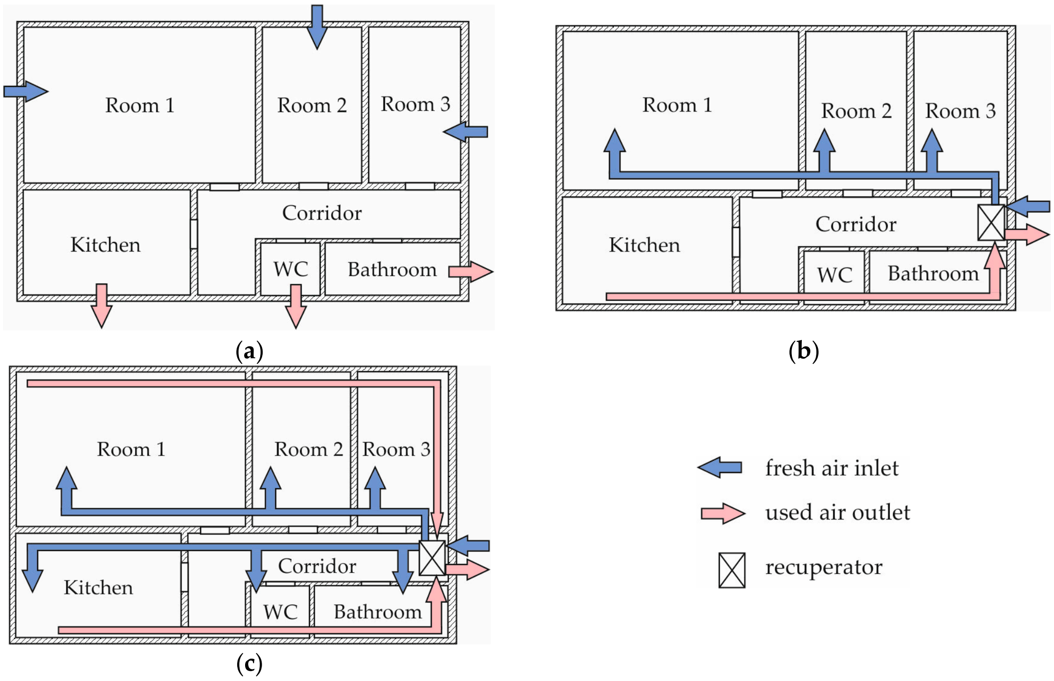
(**a**)
(**b**)
(**c**)

Figure 1. Example air flow distributions in the ventilation systems of residential buildings: (**a**) natural ventilation; (**b**,**c**) mechanical ventilation with heat recovery.

3. Results and Discussion

The test results were used to draw up graphs of variability of the carbon dioxide concentrations, relative humidity, and air temperature in the analysed objects. Having compared the graphs of air parameters variability, it was immediately apparent that the study objects with natural ventilation, i.e., apartments 2 and 3 and residential buildings 1 and 2, cannot keep concentrations of carbon dioxide below the recommended level of 1000 ppm. Also, the relative air humidity in the bathrooms and kitchens in the buildings with natural ventilation exceeded the level of 65%; such indoor humidity persists for long periods of time and may cause the growth of fungi or mould in the construction elements of the building.

Sample comparison of the variability in the concentration of carbon dioxide in apartment 1, with mechanical ventilation, and apartment 2, with natural ventilation is shown in Figure 2.

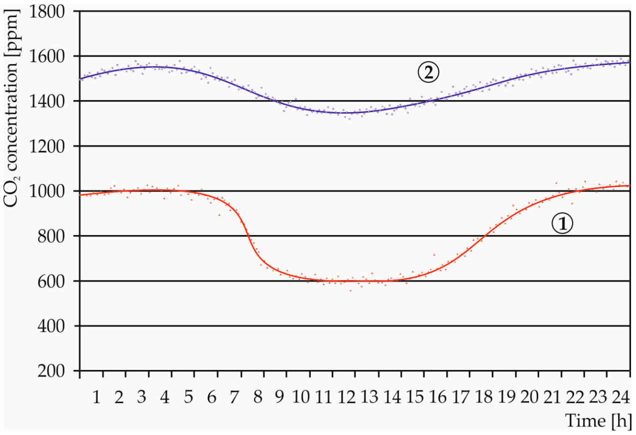

Figure 2. Comparison of the variability in the concentration of carbon dioxide in apartment 1, with mechanical ventilation, apartment 2, with natural ventilation.

Mechanical ventilation systems used in the other buildings and apartments ensured greater stability of the parameters of the air inside the analysed objects.

Table 3 presents the ventilation air streams (in column 2, determined according to Reference [22], taking into account the number of inhabitants and the number and use of rooms), averaged streams of heat lost via the ventilation system, and averaged unit heat losses via ventilation (with reference to 1 m^2 of the floorspace of the building) for the analysed research objects. These are all the data defined during the tests, calculated in accordance with the standards and by means of model equations.

Table 3. Defined ventilation air streams and heat loss for the buildings analysed.

Analysed Buildings	**Ventilation Air Stream Calculated in Accordance with the Polish Standard**	**Ventilation Air Stream Calculated with Results of Measurements**	**Ventilation Air Stream Calculated by Model Equations**	**Averaged Stream of Heat Lost via the Ventilation System**	**Averaged Unit Heat Losses via Ventilation**
	($m^3 \cdot h^{-1}$)	**($m^3 \cdot h^{-1}$)**	**($m^3 \cdot h^{-1}$)**	**($W \cdot h^{-1}$)**	**($W \cdot (m^2 \cdot h)^{-1}$)**
Apartment 1	120.0	106.1	67.5	1071.0	22.3
Apartment 2	120.0	84.2	46.9	850.0	22.9
Apartment 3	140.0	71.3	63.2	720.0	10.4
House 1	185.0	120.7	169.0	1234.0	8.2
House 2	165.0	92.6	131.2	935.0	7.7
House 3	180.0	191.3	151.4	644.0	4.2
House 4	204.0	211.8	196.4	427.0	2.1

The calculated ventilation air streams and the air parameters measured during the tests were used to create graphs for each research object to identify the optimal work parameters for the ventilation system of the building. An example graph that was used to optimise the work parameters of the ventilation system of the building (drawn for apartment 1) is shown in Figure 3.

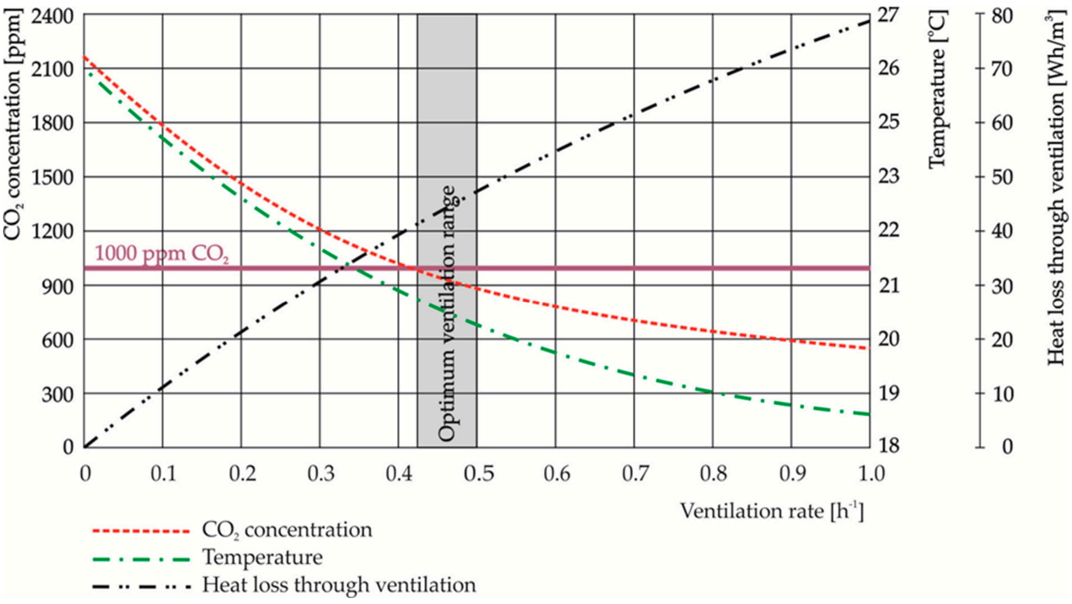

Figure 3. Example graph of performance parameters optimisation for a ventilation system in an apartment.

The measurements of carbon dioxide concentration and relative humidity in the residential buildings in the analysis indicate that there are changes in pollutant concentrations and relative humidity that are specific to weekdays, and that they affect the optimum multiplicity of air exchange in the living spaces. The optimal ventilation air stream with respect to the cubic capacity of a residential building, determined by Equation (2), allows determination of the optimal air exchange rate through the ventilation system. Figure 4 shows an example of the daily variation of the optimum rate of air exchange defined by means of the model dependencies throughout a standard weekday for residential building 2.

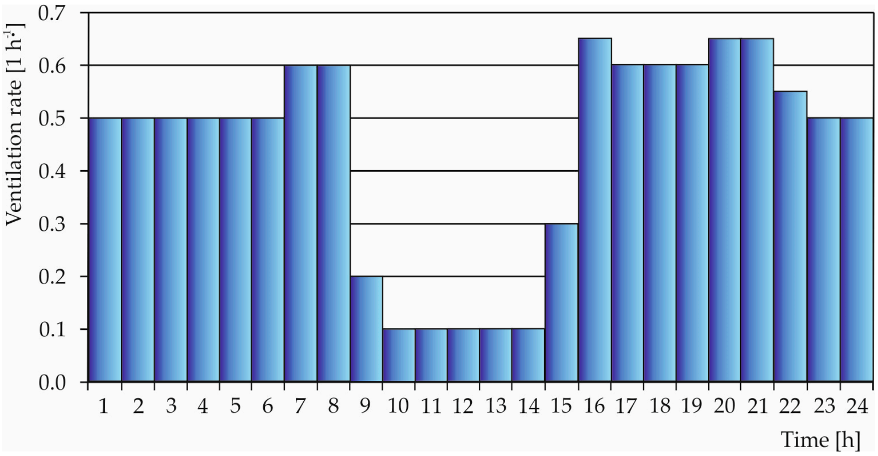

Figure 4. Optimum multiplicity of air exchange n_k throughout a standard weekday.

Graphs of the daily fluctuation of the optimum rate of air exchange were drawn for each research object, and the graphs are the basis for precise control of the parameters of mechanical ventilation systems in the objects.

It is apparent that the smallest heat loss via the ventilation system occurs with the use of mechanical ventilation—intake and exhaust with heat recovery and a ground heat exchanger. Ventilation systems with heat recovery may be implemented not only in single-family/detached houses, but also in apartment buildings. In existing apartment buildings, heat may be recovered from ventilation systems by the use of recuperators installed on the walls.

4. Conclusions

The tests show that natural ventilation should not be used in residential buildings or in communal residential buildings, because natural ventilation does not permit precise control of the ventilation airflow.

As research object 3 shows, the energy efficiency upgrade of a building (the most common type of residential building in Poland) involving only the installation of wall insulation and replacement of window joinery increases the airtightness of a building, which reduces the effectiveness of natural ventilation as well as the danger of SBS—sick building syndrome.

Mechanical ventilation by an exhaust fan meets the requirements of Polish Standards; however, due to the intermittent mode of its operation, it does not keep the concentration of carbon dioxide below the required level nor remove the excess water vapour from the air in the bathroom or kitchen.

Only the mechanical intake-exhaust ventilation system with heat recovery meets the requirements of the air quality in residential spaces, as set out in the Polish Standard PN-B-03430: 1983/Az3 2000, and at the same time minimises the loss of heat from the ventilated rooms.

This research also indicates the need to make changes in Polish regulations on construction to require the owners of residential buildings to replace natural ventilation systems with mechanical ventilation with heat recovery systems.

As can be seen in the example diagram of the variability of the optimum air exchange rate (Figure 4), it is only the control of the operation parameters of the ventilation system by changing the ventilation flow rate during the daily lifecycle of a residential building that can minimise heat loss through ventilation while maintaining the required air quality inside the building.

By determining the optimum air exchange rate for the analysed buildings by means of the suggested dependencies, it is possible to reduce the heat demand for heating of buildings by 9–12%.

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