Summary This paper describes part of a research programme on energy consumption in the Polish building sector. The work, carried out from 1980 to 1985, aimed at developing methods for measuring air flows and their influence on heat consumption in typical Polish dwelling houses. It began by establishing both experimental and theoretical methods to determine air flows in buildings. The basic measurements were done in a large number of buildings characteristic of the products of the Polish building industry and located in the Silesia region; both single-family housing and eighteen-storey apartment blocks were considered. The basic aims were to define air flow mechanisms and estimate the influence of air flow on heat consumption. The results verified previous theoretical models. The paper begins by presenting and comparing results of measurements in existing buildings. Theoretical methods are then presented, including the limitation of tightening building envelopes. The choice of ventilation systems with regard to the thermal balance of buildings is discussed.

Air infiltration and ventilation in relation to the thermal performance of dwelling houses in Poland

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1 Introduction

As well as providing protection against the outdoor climate, buildings must be designed to maintain a comfortable and healthy indoor climate. A simple and cost-effective way to realise these requirements and at the same time to save energy is to improve thermal insulation, tighten the building envelope and decrease the air change rate.

The New Polish Norm (NPN, 1983) decreased the required k values of the various building components by about 25-30%. The thermal state of a building is characterised by the average thermal transmittance of the gross enclosure area; k_m values are calculated from the k values of the various walls and their areas. The NPN encourages the thermal insulation of external walls; in Silesia the resulting work has reduced heating requirements by 10-15% in many buildings.

By contrast with knowledge on thermal transmission, the subjects of ventilation and airtightness were far less well characterised before this work started. From the energy conservation viewpoint, air infiltration and ventilation must be minimised. However, some fresh air must be supplied to a building to maintain healthy, safe and comfortable conditions for the occupants. Unfortunately, this conflict is ignored in the Polish Norms. Recent fresh air requirements have varied from 15 to 20 m^3/h per person, giving 120 to 150 m^3/h for an apartment with cooking and bathroom occupancy. In this case the air change rate varies between 0.5/h and about 2.0/h. The former is the minimum value for an average living area per person of 10–15 m^2 and room height 2.8 m[1,2]. This air change rate (0.5/h) corresponds to the ventilation rate for the building as a whole, even with periodic increases in exhaust air flow during room occupancy. This quantity of air is usually supplied by leakage in the building structure, since most houses are ventilated by natural or exhaust-mechanical ventilation (NV, EMV respectively).

On the basis of analysis of a large number of measurements on different buildings that the simple 'limitation of tightening' method and optimum choice of ventilation system can be elaborated. This method takes into account the interaction between the thermal insulation of external walls, the shape of the building and natural air flow mechanisms. Some results are presented below.

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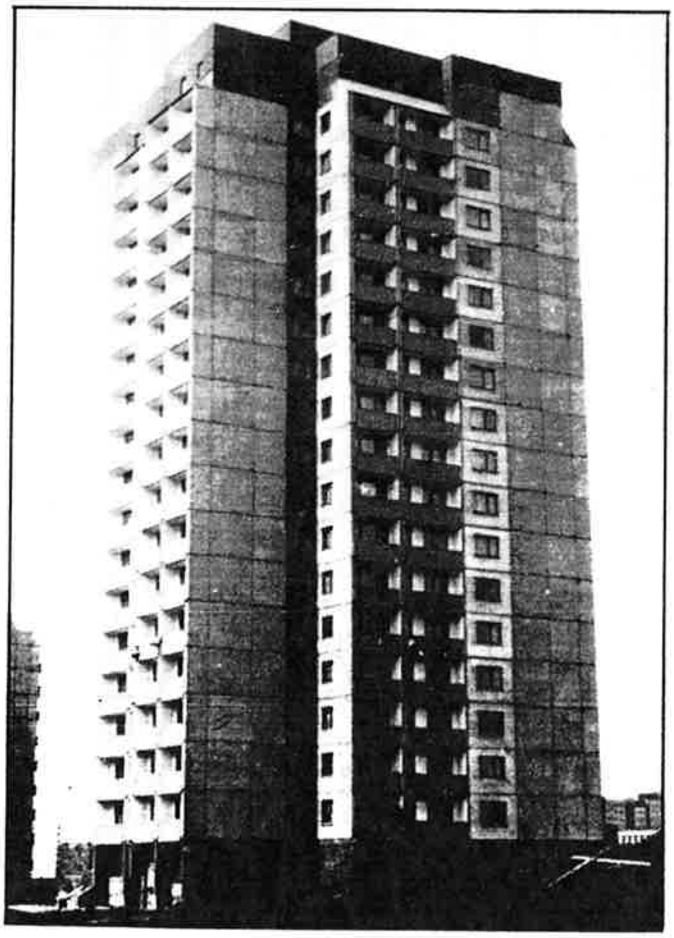
2 Results of measurements and calculations

The work was done on about 200 buildings. (Some building types are shown in Fig. 1). Work included the determination of the real insulation and tightness of various building components, air leakage through the wall assembly, the air change rate in rooms (or flats) and buildings as a whole, and determination of the heat state of buildings.

Air leakage rates for the various sections of the building (windows, doors, floor–wall joints, etc.) were measured by the underpressure technique, both in selected rooms in dwellings and in the laboratory. More than 5,000 building elements were tested. For these low-pressurisation tests a specially constructed tube from the fans was used[3,4].

In a large number of rooms (about 300) and single-family houses (about 15) the 'blower door' method was used. The blower door was mounted in the doorway with a rubber seal around the existing door frame. The door was fitted with a regulated output fan; both the pressure difference and the quantity of air from outside to inside through the wall assembly were measured in rooms without ventilation (exhaust orifices closed) and with ventilation in action[4,5].

Fig. 1. Types of buildings examined



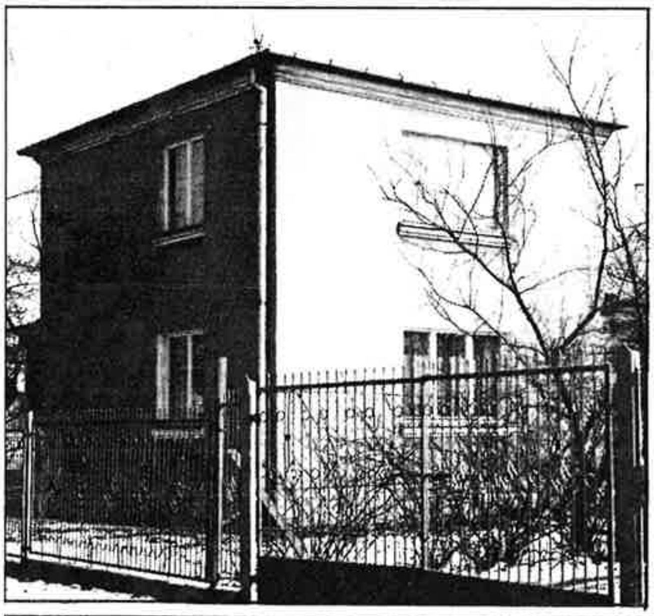


Fig. 1 continued—Types of buildings examined.

For the final year of the work air change rates were measured by monitoring the decay in concentration of sulphur hexafluoride (SF_6) and carbon dioxide (CO_2). This method has recently been adapted for use in the field. The preliminary results confirmed agreement with pressurisation test results[4,5].

For the determination of the thermal state of buildings the k values for the various building components are necessary. The thermal resistance of walls was determined from continuous measurements of heat flow through walls and temperature differences between their interior and exterior surfaces; these measurements were also useful in determining k_m for the building as a whole. Temperature, humidity, air velocity, etc. were measured simultaneously in selected rooms, as were external conditions (weather). These results, already reported elsewhere[5,6], show that there are random fluctuations, especially in rooms (or flats) located in apartment blocks with natural ventilation.

Theoretical models have been elaborated for the calculation of air and heat flows in buildings. Both the 'multi-cell' and 'single-cell' methods[4,5] were used. All measurements in existing houses verified these theoretical models, both for air flow and heat balance.

The real air change rate and thermal state of the building as a whole were determined from a large amount of data; some results of these analyses for average winter conditions are given in Table 1.

We shall now briefly discuss some results in terms of the problems of correlating air flows (or air change rates) and thermal insulation of the building envelope.

2.1 Airtightness and air change rates

Air leakage rates for building components can be presented as a relation between the specific volume of air and pressure difference (Fig. 2). The most important characteristic of a building is the air flow coefficient for various sections such as windows, doors, joints, etc. These coefficients are generally determined by air flow per unit length of gap or per unit area of building component. These values are: for

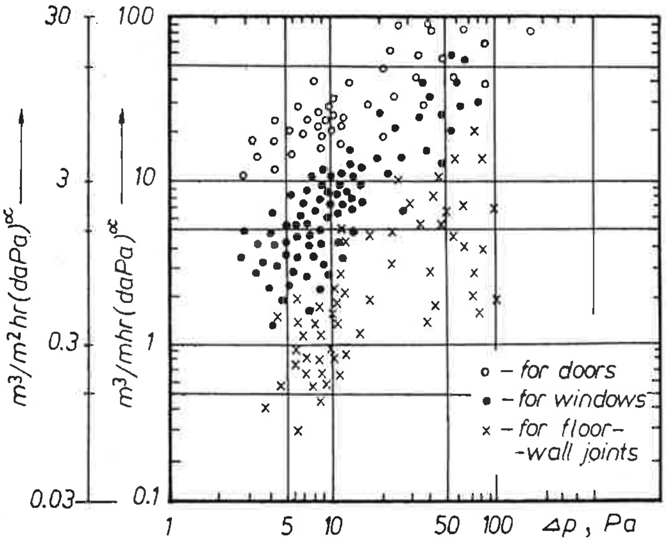


Fig. 2. Relation between specific air flow volume and pressure difference for building components

Table 1. Description of buildings tested and results of analysis.

Building type*	Vol. above ground (m³)	No. of storeys	Gross enclosure area (m³)	Window proportion of GEA (%)	D(m^{-1})	k_m (W/m²K)†	a(m³/mh)† at Δp = 1 daPa: Windows	Doors	Floor–wall joints
A(NV)	526	2	485	18.8	0.92	1.28	2.8	6.4	—
B(NV)	2300	5	1105	20.6	0.48	1.50	5.2	12.6	2.7
C(NV)	10 500	11	3200	27.6	0.30	1.65	4.8	15.1	3.1
D(EMV)	40 366	18	6155	27.2	0.15	1.81	3.7	14.4	1.9

Table 1 (continued).

Building type*	Proportion of total wall air leakage through windows (%)	n(h^{-1})‡	Δp(daPa)	Ventilation heat loss / Total heat demand (%)§	Ventilation heat loss / Total heat demand (%)¶
A(NV)	79.8	0.4	0.4–0.9	10.6	18.7
B(NV)	71.0	2.0	1.5–2.5	49.2	61.8
C(NV)	65.2	2.2	5.0–5.5	60.9	73.4
D(EMV)	75.6	1.1	7.5–15.0	58.7	71.6

*NV: Natural Ventilation, EMV: Exhaust-mechanical ventilation
†From measurements
‡For average winter conditions; Outside temp. −4–+5°C, wind velocity 1.5–3.5 m/s
§Using k_m from meaurements
¶Using k_m from New Polish Norms

windows, about 2.8 m^3/mh $daPa^{0.70}$ in single-family houses (SH), and about 4.8–5.2 m^3/mh $daPa^{0.75}$ for apartment blocks with prefabricated panels (MH). For doors: About 6.4 m^3/mh $daPa^{0.65}$ (SH) and 12–15 m^3/mh $daPa^{0.70}$ (MH).

In apartment blocks the air flow coefficients for floor–wall joints are similar to those for windows (Fig. 2). For estimation of total air leakage rates the air flow exponents are also important. The average pressure differences are 0.4–0.7 daPa (SH) and from 2.5 daPa to as high as 10 daPa (MH). The flow exponent varies between 0.58 and 0.82. In buildings with natural ventilation (all SH and some MH) the exponent is about 0.69–0.82, but in blocks with mechanical ventilation (all the high-rise buildings) it is about 0.58–0.70. For practical applications the exponent may be taken as 0.65 to 0.75 (References 3,4,5).

The air leakage rate through a wall assembly can also be obtained by measuring the air leakage through components that make up the wall. These measurements[4,5] show that windows (including window frame–wall joints) can be the main contributors, accounting for as much as 60% of the total air leakage. Next are floor–wall joints and window sills, which can account for 20% and 15% respectively.

Some results of measurements of the air change rate in single rooms and buildings are illustrated in Figs. 3 and 4 (by the 'blower door' and tracer gas methods). The air change rate for the whole building in winter is 0.1–0.4 h^{-1}

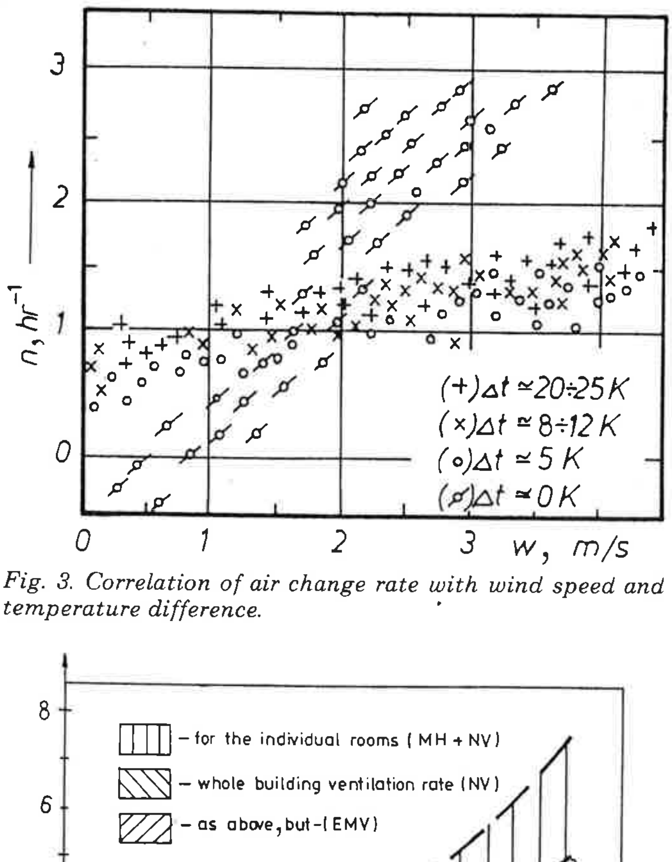


Fig. 3. Correlation of air change rate with wind speed and temperature difference.

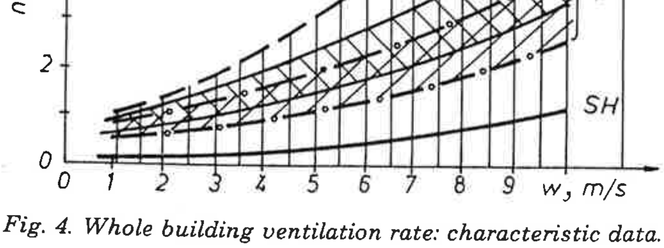


Fig. 4. Whole building ventilation rate: characteristic data.

(SH) and up to 2.2 h^{-1} (MH) with natural ventilation. In buildings with exhaust-mechanical ventilation (MH only) the air change rate varies between 0.8 h^{-1} and 1.5 h^{-1}.

The air change rate in a building without ventilation (if exhaust orifices are closed) decreases by about 40% (SH) and about 20% (MH) when natural ventilation is applied. For individual rooms the supply of outdoor air through a wall assembly varies between −45 m^3/h (air exfiltration) and higher than +150 m^3/h (air infiltration). If exhaust-mechanical ventilation is applied this quantity of air is from +20 m^3/h to +100 m^3/h (air infiltration only). In this case, the air change rate without ventilation (if fans are switched off and exhaust orifices are closed) decreases by about 80%-90%.

Finally, both the overall air leakage rate and total ventilation rate are functions not only of natural or mechanical action, but also the size of the building, its shape, location in the terrain and structure.

2.2 Energy consumption and ventilation heat losses

Total energy consumption varies between 30 and 45 MWh per heating season for the single-family houses tested, and is higher than 1,000 MWh per heating season (MH). Energy for heating and ventilating buildings constitutes a substantial proportion of all consumption. Heat losses as the sum of conduction and the heat flow due to the air infiltration and ventilation constitute about 75–80% of a building's energy balance. These heat losses may be characterised by the average thermal transmittance of the gross enclosure area (k_m values) and the air change rate per hour for the whole building (n values).

The average k_m values vary between 1.1–1.4 W/m^2K (SH) and 1.3–1.8 W/m^2K (MH). These data allow estimation of the fraction of the heat loss which is due to ventilation (Table 1). For buildings with natural ventilation this fraction varies between 10–12% (SH) and 40–60% (MH). In blocks with exhaust-mechanical ventilation the fraction is always higher than 50%. In general the heat consumption ventilation processes in average winter conditions varies from 10–25 MWh (SH) to as high as 450–750 MWh (MH) per heating season. This fraction is increased by additional external wall insulation to 15–20% (SH) or even 75% (MH).

Finally, the ventilative heat losses are characterised both by the rate air infiltration ($\Sigma \dot{V}_{IN}$) and air change rate per hour (n). The air leakage rates of walls, including the effect of any ventilation system, vary considerably, with values of 6 to 10m^3 per m or 2 to 3.5 m^3 per m^2 of wall area at a pressure difference of 5 daPa.

2.3 Theoretical study of air and heat flows

Airtightness and the type of ventilation installed are important both for the determination of air flows and for energy consumption in buildings. In many countries the fruits of several years' experience can now be observed, both of testing buildings, and also of air and heat flow simulation[7,8]. The best analysis method is the digital computer program based on air flow, pressure drop balance and weather data for a reference year. These methods have been used here; the constructional elements of buildings and also parameters of ventilation systems were taken into account[9]. The large number of calculations, confirming the results of measurements in existing buildings, provide enough information to describe the heat state of the building as a whole. The total heat demand can be expressed by the function

$$\dot{Q} = f(k_m, a_m, n_v)|_{\text{for } C_1, C_2} \quad (1)$$

where n_v is the air change rate, a function only of the type of ventilation system, and C_1, C_2 are the reference conditions.

These conditions are determined by the geometric and constructional properties of buildings (C_1) and the forces acting on the building envelope (C_2). The function (1) can be evaluated by determining the average k_m values and the average air flow coefficient of the gross enclosure area, i.e. the a_m values. These a_m values result solely from the action of natural forces such as stack and wind effects (without a ventilation system). On the other hand, the k_m and a_m values may be determined through permissible indoor climate parameters[2,10,11].

The thermal transmittance varies between 0.3 W/m²K and 0.4 W/m²K (for walls) and as low as 2.0 W/m²K (for windows). The k_m value is a function of these values and of the external wall areas.

The building components must be tight, and the greater part of the air supply restricted to the windows. The coefficient of air flow for typically sized windows in Polish housing varies between 1.5 and 1.8 m³/mh at a pressure difference of 1 daPa. From the viewpoint of the thermal environment, the air velocity in the vicinity of windows of dimensions 0.3–0.4 m cannot be higher than about 0.1 m/s, i.e., the velocity characteristic of the convective flux of man's body[12]. In practice, these values depend on the pressure difference acting across the building's structure and its location in the terrain. Therefore, the a values are derived from thermal buoyancy and wind driving.

The total air change rate in buildings as a whole is 0.5/h. This minimum ventilation rate depends both on tightening the building envelope and the type of ventilation system.

Energy consumption and the limitation of heat reduction are important considerations in determining these three groups of factors and their interconnections. Section 3 presents a simple method to connect these factors.

3 Proposed method for choice of ventilation system

The design of ventilation systems for dwelling houses embraces not only the power source (fans) and construction detail of air ducts, but also the airtightness of the building structure. None of these factors, however, takes into account the main point which is the quality of ventilation—but good ventilation cannot be obtained without tight structure. We propose to answer many questions, including the following:

(a) What types of ventilation system should be applied to different dwelling-houses?

(b) Where is the limit in tightening the building envelope?

(c) How can the correlation between airtightness, air change rates and thermal performance be determined?

These questions are relevant for all countries seeking to reduce energy consumption in the building sector. Current data for the analysis of these problems are results of the early measurements done in existing buildings, and resulting mathematical models; these dealt with air flow and heat balance simulation.

The total heat demanded for a building as a whole can be expressed as

$$\dot{Q}(\text{T}) = \dot{Q}(\text{CHF}) + \dot{Q}(\text{NAF}) + \dot{Q}(\text{MV}) \qquad (2)$$

where $\dot{Q}$(CHF) is conductive heat loss, $\dot{Q}$(NAF) is heat loss connected with natural air flows from outside to inside, and $\dot{Q}$(MV) is heat demand resulting from mechanical ventilation.

The first and second terms of equation (2) are decisive for the thermal protection of buildings (they are attributable to natural forces, the indoor-outdoor temperature difference and wind pressure). The second and third terms of the equation result both from natural and mechanical air flows.

The terms on the right-hand side of equation (2) are given by:

$$\dot{Q}(\text{CHF}) = k_m A_z \Delta t$$

$$\dot{Q}(\text{NAF}) = \Sigma \dot{V}_{iN} c_\varrho \Delta t$$

$$\dot{Q}(\text{MV}) = n_v V c_\varrho \Delta t \qquad (3)$$

where $\Sigma \dot{V}_{iN}$ is the total air filtration (m³/h), n_v is the air change rate as a function of the power and construction of the ventilation system (/h), c_ϱ is the specific heat capacity of air (on average 0.36 Wh/m³K), V and A_z are the building volume and total area of building envelope respectively and Δt is temperature difference (K).

The total air infiltration may be expressed by the formula

$$\Sigma \dot{V}_{iN} = a_m A_z (\Delta p_m)^\alpha \qquad (4)$$

where a_m is the average air flow coefficient of the gross enclosure area (m³/m² h daPa$^\alpha$, Δp_m is the average pressure difference (daPa), and the air flow coefficient α is usually near 0.7.

The average pressure difference may be calculated as a mean from pressure differences on the various external walls, weighted by area. 'Single-cell' models were used for these calculations. The air flow calculations were verified both by the air flow calculation from 'multi-cell' models and the principal measurements on existing buildings.

On the basis of equations (2), (3) and (4) the heat losses connected with the thermal protection of buildings may be given by:

$$\dot{q}(\text{TP}) = k_m + a_m \Delta p_m{}^\alpha c_\varrho \qquad (5)$$

and the heat demand from natural and mechanical air flows by

$$\dot{q}(\text{ACR}) = (a_m \Delta p_m + n_v D^{-1}) c_r \qquad (6)$$

where the $\dot{q}$ values are heat losses per unit temperature difference and D is the ratio of gross enclosure area to the building volume.

Equations (5) and (6) can be the basis for deciding the limit of tightening, the type of ventilation system, and also their connection with the average thermal insulation of the gross enclosure area. On the basis of an analysis of indoor climatic requirements, the heat losses connected with the uncontrolled air flow $\dot{Q}$(NAF) must be less than or equal to 25% of the conductive heat flows[11]. Simultaneously, the total ventilation rate must be about 0.5/h.

If the fraction of heat losses due to the uncontrolled air flow through natural infiltration is reduced to 20% from the sum of $\dot{Q}$(CHF) and $\dot{Q}$(NAF) values, the average air flow coefficient may be expressed by

$$a_m = 0.7\, k_m (\Delta p_m)^{-\alpha} \qquad (7)$$

Fig. 5 illustrates equation (7) for typical Polish dwelling-houses.

Buildings are divided according to the value of D, the ratio of the gross enclosure area to total volume. The average air flow coefficients are functions of aerodynamic conditions, i.e. the pressure differences characteristic of different buildings, their location in the terrain and the thermal insulation of external walls. The data shown on Fig. 5 are representative for free-standing buildings (curves 2 and 3: Δp_m^{max}) and buildings situated in towns (curves 1 and 2: Δp_m^{max}). As shown, the a_m values for apartment blocks vary between 0.15 and 0.40 m³/m²h daPa$^{0.7}$ if k_m values conform to the New Polish Norm (curve 2). For real k_m values (curve 1: measurement results) this coefficient

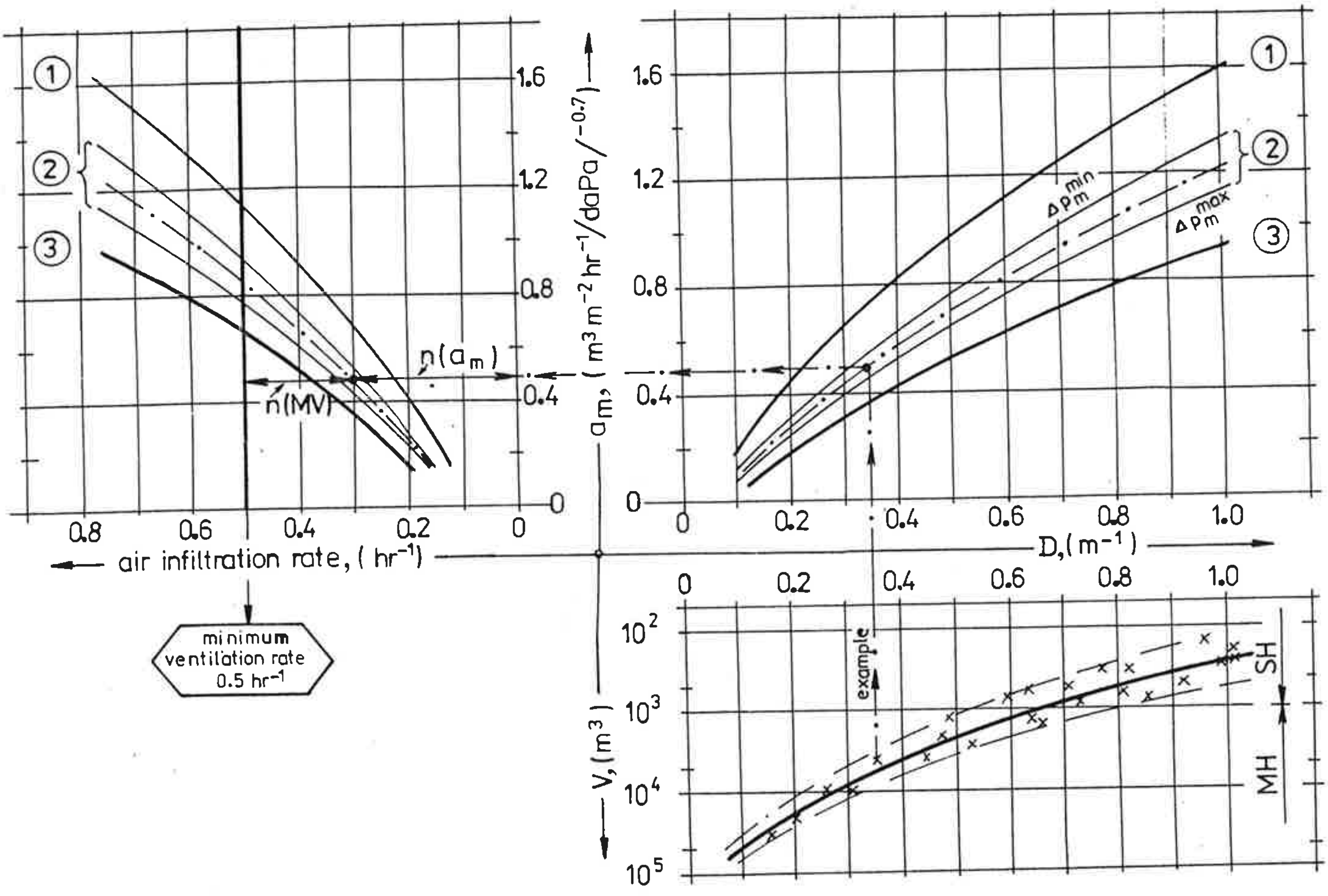


Fig. 5. Behaviour of the average air flow coefficient for the various building types.

equals 1.0–1.2 $m^3/m^2h\ daPa^{0.7}$. Curve 3 represents the optimum comfort requirements.

These a_m values may be determined per m of the total length of gaps in windows:

$$a_0 = a_m (\varphi_0\, \eta_0\, s_0)^{-1} \tag{8}$$

where a_0 is the air flow coefficient (m^3/mh at $\Delta p = 1$ daPa a_m is the average air flow coefficient from Fig. 5 (m^3/m^2h) at $\Delta p = 1$ daPa,
φ_0 is the ratio of window area to the gross enclosure area, η_0 is the ratio of air leakage through windows to total air infiltration, and s_0 is the ratio of the total length of gap in windows to their areas (/m).

For typical windows in Polish houses, s_0 averages about 3.5. In practice η_0 varies between 50% and 60%, and for 'tight' buildings should be 0.90–0.95. For these data the average air flow coefficient per m of length of gaps in windows can be expressed as follows:

For the real buildings (curve 1):

$$a_0 = 0.48\, a_m \varphi_0^{-1} \tag{9a}$$

For the rules of Polish Norms (curve 2):

$$a_0 = 0.36\, a_m \varphi_0^{-1} \tag{9b}$$

In future buildings (for optimal comfort requirements—curve 3):

$$a_0 = 0.30\, a_m \varphi_0^{-1} \tag{9c}$$

Equations (8) and (9) determine requirements for tightening windows. For the average values of the ratio φ_0 (about 0.25—see Table 1) the a_0 value is about 2.3 m^3/mh $daPa^{0.7}$. The real a_0 values are higher than the above-mentioned ones by about 60%–100%, but in this case the total ventilation varies between 1.5/h and more than 2.0/h(MH).

Fig. 5 shows a high average air flow coefficient for single family houses and that the air velocity near windows is greater than the air velocity characteristic of the convective flux of the human body. Therefore the maximum a_0 values can be determined for characteristic percentages of window area together with equations (8) and (9). These values must be equal to or lower than about 0.8 m^3/m^2h at $\Delta p = 1$ daPa[12].

For buildings with D less than 0.6–0.7/m the average air change rate is also lower than the minimum ventilation rate. These buildings are excessively hermetic, and the supply of fresh air is not satisfactory. Therefore, if the building's volume is greater than 1,000–1,200 m^3, mechanical ventilation must be installed. In this case, the total air change rate is the result both of natural forces and of the power of mechanical ventilation. The total air change rate is given by:

$$n(a_m) + n(\mathrm{MV}) = [2.8/(1-\psi)]k_m D \tag{10}$$

where $n(a_m)$ is the air change rate only due to natural air flows (expressed through the a_m value), thermal buoyancy and wind effects, n(MV) is the additional air change rate due only to mechanical ventilation (controlled systems), and ψ is the ratio of the sum of the ventilation heat losses to the total heat demand.

The additional air change rate is a function of building size (through D) and the a_m value. This air change rate can be as high as 0.4/h if the D is 0.15/m, i.e. for high buildings. These n(MV) values are shown also in Fig. F5 (top left). The increase of air change rate accompanies an increase of the ratio ψ, but these changes are periodic (two or three hours a day as deduced from measurements and questionnaires on existing houses). This is characteristic for high-rise buildings ($V > 15\ 000\ m^3$), for which the ratio ψ equals about 40%–45%. This ratio may be reduced to about 20% with a ventilation system independent of weather conditions and allowing of air flow regulation. The use of exhaust-mechanical ventilation only improves the efficiency of ventilation ducts: the supply of outdoor air through gaps in windows (and thus the heat demand) is uncontrolled. Besides EMV, the supply-exhaust mechanical system (SEMV) may be installed. These systems can be combined with heat recovery from the exhaust air. Table 2 shows some results of calculations for average winter conditions (0°C, 5 m/s). The table shows that the reduction of ventilation heat losses can be reduced by 45% (SH) or even 70% (MH—with waste heate recovery).

Finally, energy reduction by eliminating excessive air flow through the building envelope may be limited to about 20% of the total heat demand for the thermal protection of buildings.

4 Application

On the basis of experimental and theoretical studies of airtightness and ventilation in buildings, and their influence on heat losses, basic criteria for the correct designing of dwellings can be drawn up. Fig. 6 shows the practical application of proposed method; the graph allows determination of the limit of tightening of external walls (top) and the choice of ventilation systems[13].

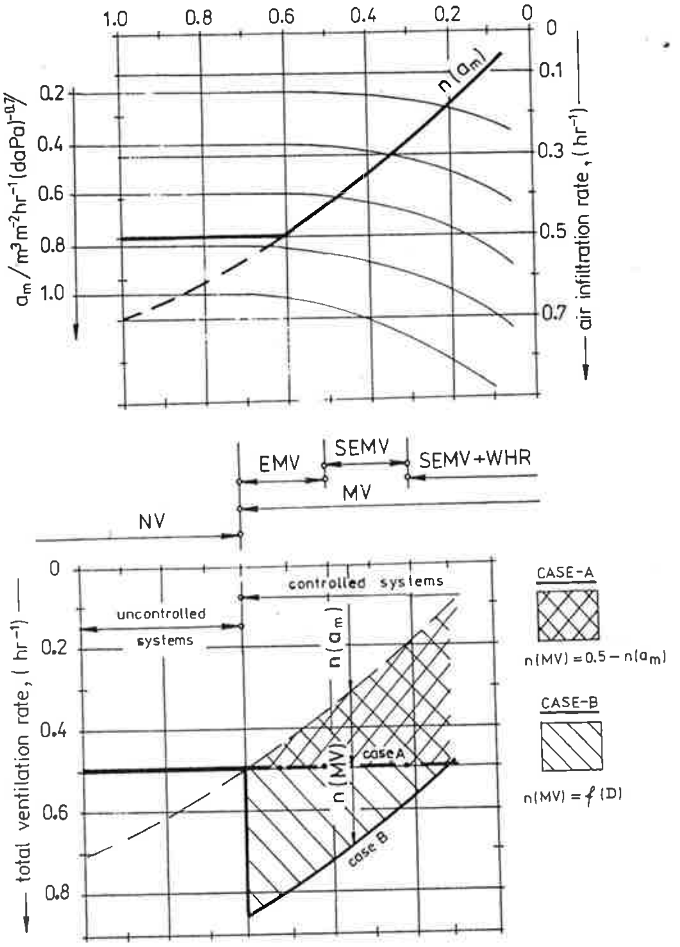


Fig. 6. Illustration of proposed method for choosing ventilation systems for dwellings.

4.1 Natural ventilation NV

This system can be recommended if the building volume is lower than 1200 m³ and the ratio D is higher than 0.6/m. The average air flow coefficient varies between 0.6 and 0.8 m³/m²h daPa$^{0.7}$. For a typical ratio of window area to gross enclosure area in these buildings φ_0 = 0.10–0.15, the air flow coefficient for windows is 1.8–2.5 m³/mh daPa$^{0.7}$. The fraction ψ is always less than 20%.

4.2 Exhaust-mechanical ventilation EMV

These systems are recommended for building volumes less than 6000 m³ where ratio D varies between 0.4 and 0.6/m. The average air flow coefficient is about 0.5–0.6m³/m² h daPa$^{0.7}$. For a typical φ_0 = 0.20 the air flow coefficient for windows varies between 0.75 and 1.0 m³/mh daPa$^{0.7}$. The total ventilation rate may be about 0.5/h (case A on Fig. 6) or about 0.7/h (case B). In these cases ψ is about 20%.

Table 2. Results of calculations for the buildings described in Table 1.

Building type	k_m (W/m²K)		n(h⁻¹)*		Ventilation heat losses (MWh/year)†			
	(1)	(2)	EMV	SEMV	(3)	EMV	SEMV	SEMV+WHR‡
A	0.81	0.53	0.43	0.25	13.9	15.0	8.7	4.3
B	0.90	0.57	0.44	0.28	305.9	67.3	42.8	21.4
C	0.93	0.62	0.47	0.32	1536.2	328.2	223.4	111.7
D	1.02	0.63	0.50	0.35	2952.8	1342.2	939.6	469.8

(1)Optimum for a medium energy price increase
(2)Optimum for a high energy price increase
*These values are for an average air flow coefficient of the gross enclosure area of about 0.5 m³/mh daPa. The power density of air infiltration through these windows varies from 0.01 to 0.1 mW/m³.
(3)From measurements
† Includes air infiltration
‡ Where heat recovery (WHR) efficiency is about 50%

4.3 Supply exhaust-mechanical ventilation SEMV

These systems are recommended for high-rise buildings when the D ratio is lower than 0.4/m.

(a) If a building's volume is lower than 10 000–12 000 m^3 and the ratio D is higher than 0.20–0.25/m, the ratio ψ varies between 20% and 30%. On the basis of recent economic considerations, a decrease in this fraction can be tolerated, provided air can be regulated in the supply and exhaust ventilation ducts. The a_m values vary between 0.3 and 0.4 $m^3/m^2h\ daPa^{0.7}$ and the a_0 values for windows are about 0.35 $m^3/mh\ daPa^{0.7}$

(b) For high buildings ($D < 0.2/m$) supply exhaust mechanical ventilation with waste heat recovery (SEMV + WHR) is recommended. The average air flow coefficient must be 0.1–0.2 $m^3/m^2\ h\ daPa^{0.7}$ (these coefficients for windows and $\varphi_0 = 0.40$ are similar to the quoted values). These values are minimal in terms of the dimensional tolerances of windows fitted in Polish dwellings.

These recommendations are also indicators for determining the method of heat consumption reduction. Correct solutions of the building's envelope and the type of ventilation reduce the heat consumption by 10%–20% (in buildings with natural ventilation—not more than three or four storeys) or even 40%–50% in apartment blocks.

5 Conclusion

Air flow and airtightness are important not only in determining and defining the thermal environment in dwelling-houses, but also for energy consumption. From analysis of many experiments in existing buildings we have elaborated a simple method for reducing ventilative heat losses. This simplification is valuable both from an energy conservation point, and in achieving healthy and comfortable indoor living conditions. It assists in defining the limit of tightening the building structure and in choosing the best type of ventilation.

References

1 Lindvall T., Minimum ventilation rates—biological demands. Slutrapport No. 4/81, The National Institute of Environmental Medicine, Stockholm (1981).

2 ASHRAE Standard 62-81, Ventilation for Acceptable Indoor Air Quality. Atlanta (1981).

3 Nantka M.B., Tightness of Prefabricated Outer Walls and its influence on Heat Demanded in Apartment Buildings. Air Infiltration Review No. 2 (1983).

4 Nantka M.B., Theoretical and Experimental Study of Heat Flows due to the Air Infiltration and Ventilation. Proc. 7th International Conference VHC'84, Prague (1984).

5 Nantka M.B., Ventilation and Heat Losses in Buildings. Proc. 4th International Conference HVAC'84, Varna (1984).

6 Nantka M.B., Ventilation and Air Infiltration in Relation to the Indoor Air Quality and Energy Consumption of Typical Polish Buildings. Proc. 3rd International Conference on Air Quality '84, Stockholm (1984).

7 Ross H.D. and Grimsrud D.T., Air infiltration in buildings: Literature survey and proposed research agenda (Draft). International Energy Agency, November (1977).

8 Liddament M. and Allen C., The Validation and Comparison of Mathematical Models of Air Infiltration. Technical Note AJC 11, Air Infiltration Centre (1983).

9 Nantka M.B., Calculation Methods for the Natural and Mechanical Ventilation in Dwelling-houses. Silesian Technical University Reports (unpublished) (1984).

10 Fanger P.O., Human Comfort and Energy Consumption in Residential Buildings. International Conference on Energy Use Management, Tucson (1977).

11 Petersen F., Byggnad, byggnadsdler och inre försorjnings—system. Programplan EFUD 02, Institut-KTH, Stockholm (1978).

12 Mierzwiński S., Air motion and temperature distribution above human body in result of natural convection, Institut KTH, A-4-serien nr 45, Stockholm (1980).

13 Nantka M.B., Air flow in dwelling-houses from an energy point of view: Polish experience. Proc. of World Congress on HVAC, CLIMA 2000, Copenhagen (1985).