A STUDY OF AIR INFILTRATION AND NATURAL VENTILATION IN DWELLING HOUSES

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In many countries research workers some analyses of buildings for the airtightness and also the estimation of air infiltration and ventilation. A theoretical and experimental study of these processes has also been undertaken by the author since 1980. This paper presents some of the results of this study for typical dwelling houses with the natural ventilation systems.

INTRODUCTION

The majority of dwelling houses in Poland are ventilated by the natural ventilation. This type of ventilation is widely used in the Polish building industry in blocks smaller than eleven - storeys dwelling houses. For interior rooms, e.g. kitchens, bathrooms and toilets exhaust ventilation by the individual (single - family or small houses) or collective (multi - family blocks) shafts without fans are often found. In this system, the air infiltration takes place not only through windows or gaps around windows or doors, but also through different joints in building enclosure.

From the point of view of energy conservation the air outflow due to air infiltration have to be minimized [1,2]. However, some fresh air must be supplied to a building to keep healthy, safe and comfortable conditions for the occupants [1,3]. This air is usually supplied by leakage through the building structures, e.g. from outside to inside. Therefore, the most important problem is the proper fulfilment of these conflicting requirements.

The paper describes a part of the research programme on airtightness, air infiltration and ventilation in Polish building sector. In the first part of the paper some results of measurements and calculations are presented and compared. On the basis of analysis of a large number of measurements on different buildings that the simple limitation of tightening method and optimum choise of ventilation system can be elaborated. This method will be presented below.

SCOPE OF WORK AND RESULTS

The research work has been done in about 80 building with outdoor air supplying by natural ventilation; they are both single - family houses and eleven - storeyed multi - family blocks. All tested houses are made from prefabricated panels with the mineral wool. The characteristic data of the construction of these buildings are shown in Table 1. Internal layout of these houses is typical and shown on Fig. 1,2 and 3.
The work, carried out from 1980 to 1985, with the aim of developing methods for measuring air flows and their influence on heat consumption and also thermal comfort in dwelling houses [4]. Basic aim of these measurements was the determination of the real airtightness and air change rates in tested buildings.

Table 1. Description of tested buildings

Specifications	No. of floor levels above ground		
	2	5	11
Year constructed Year tested(1)	1979 1982-4	1976 1983-5	1972 1983-5
Volume above ground, V, m^3 Total outside wall area, A_z, m^2 (2)	368,0 390,0	4540,0 1770,0	10500,0 3156,0
Floor plane, m x m Storey height, m	12,89 x 10,09 2,75	28,00 - 11,55 2,52	28,80 x 17,19 2,55
Typical window size, m x m Window plane, % wall area	1,51 x 0,91 22,5	1,51 x 1,51 27,8	1,51 x 1,51 52,3
Type and dimensions of air ducts, cm x cm	Individual ducts 14 x 14	Collective ducts branch of collective 37,0 x 21,0 21,o x 13,0	 49,0 x 21,5 21,5 x 19,0
Window type	Operable double glazing in wodd (normally locked)		
Wall construction	Precast concrete panel (with 2-6 cm insulation)		

(1) Number of tested buildings: 20 (2 floor levels), 34 (5 floor Levels) and 26 (11 floor levels)

(2) Including windows

METHOD USED. In order to measure air leakage rates for the various elements of the building (windows, doors, floor - wall joints, etc.) the underpressure technics was applied. For these small - pressurization tests the special tube construction (from fans) was used [4,5]. In the large number of rooms (about 300) and single - family houses (about 19) the "blower door" method was used [4,6]. The measurements were made in rooms or flats without ventilation (exhaust orifices closed) and with ventilation in action [4,5,7]. In the last period of measurements (2 years) the air change rates were measured by monitoring the decay in concentration of sulphur hexafluoride (in occupied dewellings) and carbon dioxide (in unoccupied). The preliminary results confirm agreement with pressurization test results [4,6]. In order to measure the air flows in ventilation orifices an anemometer was used [4,8].

Theoretical models have been elaborated for the calculation of air flows and air exchange in rooms and buildings. One of the best methods for estimation of these values is the digital computer programme based on air flow, pressure drop balances and weather data for a average year ('reference year'). These methods have been used here; the constructional elements of building and also parameters of ventilation systems were taken into account [4,6,7,9].

RESULTS OF MEASUREMENTS. Air leakage rates for a building components can be presented as a relation between the specific volume of air and pressure difference. These results for a different building components are illustrated on Fig.4. The most important characteristic of a building is the air flow coefficient for the various sections such as windows, doors, joints, etc. These coefficients are generally determinated by air flow per unit lenght of gaps or per unit area of building component. These values are: for windows, about 2.8 m^3/mh at 1 daPa in single - family houses, and about 4.8-5.2 m^3/mh at 1 daPa multi - family buildings. For doors: about 6.4 and 12-15 m^3 mh at 1 daPa, respectively for single- and multi - family houses. The air flow coefficients for floor - wall joints are similar to these for windows and are about 1.0-1.5 m^3/m^2 h at 1 daPa.

The air leakage rate through a wall assembly can be also obtained by measuring the air leakage through components that make up the wall. These measurements show that windows (including window framewall joints) can be the main contributors for as much as 60% of the total air leakage.

The investigation of the natural ventilation operation shows that external and internal conditions and also structural properties of the building are the factors that deforme air exchange.

In tested dwelling housese, especially in 5- and 11-storeys buildings, the dependence of flowing air quantity and flats location on the height intensifies with lower external temperature and wind velocity. It refers both to air infiltration and air exhaustion. Ventilation ducts in the flats located in the upper part of buildings generate underpressure that in the flats at the bottom of blocks. Those factors cause air flowing through the stairway from the bottom to the top of it. This is characteristic for unoccupied buildings and for winter season (if the wind velocity is lower than 1.0 m/s).

In occupied buildings located in towns the greatest changes take place in houses shielding by others. In flats located on top of these houses exterior air does not flow in (see on the probability of pressure differences in Fig.2 and 3). For example, air exfiltration through windows located from second to fourth storey (if the wind velocity is small) and from six to seven (when the wind velocity is higher than 3 m/s). In practice, the air temperature in ventilation ducts is higher than the indoor air temperature (in average, about 1-2 K). In this case, the paths of air flowing on the stairway change. Ventilation ducts generate larger underpressure in the bottom flats and motion of the air on stairway is from the top of building, to the bottom. Simultaneously, in ventilation ducts for the top flats, the direction of air flowing changes. This reverse air flowing zone depends on the directions wind velocities. In average winter conditions, e.g. outdoor air temperature, about 0°C and wind velocity 3-5 m/s, this zone may include four to six upper most floor-levels in eleven-storey blocks and one to three the upper floor-levels in five-storey houses. In low houses (see Fig.1) these changes are lower than the mentioned ones.

The air exchange in buildings without ventilation, e.g. when exhaust are closed, are decrased about 40% in single - family houses with the individual ventilation ducts and about 20% in multi - family buildings with the collective ventilation ducts. The total ventilation rate as the whole buildings in winter season is 0.1 - 0.4 per hour (in small houses) and about 2.2 per hour (in multi - family blocks).

Finally, both the overal air leakage rates and total ventilation rates are the function not only of natural forces as stack and wind effects, but also the size of buildings, their shapes, location in the area and structure of these buildings.

RESULTS OF CALCULATIONS. The basic mathematical model is a simulation of all paths in the building (cracks, joints, ventilation ducts and other openings). The principles of this 'multi-cell' model and particular results has already been presented in a previous work [4,6,7,9]. Therefore, in this paper only the general conclusion are presented.

The most characteristic for discussed processes are calculation results for eleven - storeys buildings. In these blocks the dependence of flowing air quantity and flats location on the height of buildings intensifies if the external temperature is lower 0°C and the wind velocity is lower than 1.0 m/s (as in the real buildings).

If the wind velocity is higher than 1.5 m/s the relationship between air infiltration and pressure differences is non-linear. For wind velocities lower than 1.5 m/s this relationship is linear. Between 0 m/s and 1.5 m/s and temperature difference 10 K (and higher), buoyancy effect dominates. Between 1.5 m/s and about 3.0 m/s the influence of both buoyancy and wind interacts. When buoyancy effect dominates, the air change rate vary between 0 and 2.0 per hour for a single flat.

These results are calculated in the situation with all windows and doors are closed and the air flow coefficients are equal 5 m^3/mh at 1 daPa (for windows) and 15 m^3/mh at 1 daPa (for doors). If these coefficients are lower than these values, e.g. for windows about 1.0 m^3/mh at 1 daPa, and 0.5 m^3/mh at 1 daPa - for doors, the air infiltration is reduced from 48% (for average weather conditions in winter - 0°C, 3-5 m/s) to 20% for designing conditions, e.g. +12°C, 0 m/s. Changes of air flowing in smaller buildings aproximate those of the above mentioned eleven-storeys buildings [6,7].

Results of measurements and calculations of air change rates prove that there are accidental conditions in the buildings with the natural ventilation. The air leakage rates of the building enclosure vary considerably, with values of 6 m^3 to 10 m^3per ´m´ or of 2 m^3 to 3.5 m^3 per ´m sq.´of wall area at the pressure difference of 5 daPa. In such cases, the total ventilation rate varies between 0.5 and about 2.0 per hour. For the individual flats these values are lower (air exfiltration) or higher than mentioned ones. Differences between results of measurements and calculations are the consequence of the negligence air flow through floors and ceilings of flats or buildings. The accuracy of this calculation depends on the correct assesment of airtightness distribution upon all perpendicular and horizontal walls of buildings [10].

BUILDING AIRTIGHTNESS LIMITATION

One of the simple mathematical models for calculations of air infiltration is the ´single-cell´ model. In this case, the building is represented by a rectangular prism [10]. The rate of supply of outside air equals the sum of air leakage rates through the exterior walls of typical floors (vertical surfaces), bottom and top seperation (horizontal areas). On the other hands, the total air infiltration may be expressed by the basic relationship between the leakage of buildings envelope and the average pressure differences,

$$\Sigma \dot{V} = a_m A_z (\Delta p_m)^{\alpha} \qquad (1)$$

In this equation, Δp_m is the average pressure difference which is characteristic for buildings envelope, a_m is the average air flow coefficient of the gross enclosure area (m^3/m^2 h at 1 daPa), A_z is the total area of all external walls, and α is the flow exponent (usually near 0.7).

THE METHOD. The average pressure difference may be calculated as a mean from pressure differences on the various external walls ($\Delta \overline{p}_i$), weighted by area. This Δ pm - values may be given by:

$$\Delta p_m = \phi \Sigma \Delta \overline{p}_i (A_i/A_z) \qquad (2)$$

where A_i/A_z is the ratio of the i-th wall area to the gross enclosure area, and ϕ is the correction factor which is function both the internal resistance to air flow and the natural ventilation actions. This factor vary between 1.2 - for houses without corridors and with the individual ventilation ducts, and about 1.3-1.4 - for buildings with corridors and with the collective ventilation ducts [9,10].

When the $\Delta \overline{p}_i$- and Δp_m - values are known, the average air flow coefficient can be determined as follows

$$a_m = \sum a_i \ (A_i/A_z) \ (|\Delta \bar{p}_i| \ / \ |\Delta p_m|) \ \text{sgn}(\delta \Delta p) \qquad (3)$$

where a_i is the air flow coefficient for the i-th external surface. Both the a_i- and a_m-values are determinated by air leakage per 'm s q.' of the total wall area. These values may de defined also per 'm' of the total length of gaps in windows. It is possible by equation:

$$a_o = a_m \ (\varphi_o \eta_o \ s_o)^{-1} \qquad (4)$$

where a_o is the air flow coefficient in m^3/mh at 1 daPa, a_m is the air flow coefficient in m^3/m^2 h at 1 daPa, φ_o is the fraction of windows area to the building's envelope, e.g. $\varphi_o = A_o/A_z$, η_o is the ratio of air leakage through windows to the total air infiltration- as results of measurements in existing dwelling houses or as effects of predictions for future buildings tight houses and s_o is ratio of the total lenghth of gaps in a typical window area (in m^{-1}).

For typical windows in dwelling houses the ratio s_o is in average about 3.5 m^{-1}. In existing buildings, the ratio η_o varies between 50% and 60% [4,6]. For future houses (tight buildings) this ratio must be about 90-95%. For the above-mentioned data the a_o-values can be expressed as follows

- For the real state of buildings

$$a_o = 0{,}5 \ a_m \ (\varphi_o)^{-1} \qquad (5a)$$

- For future (tight) buildings

$$a_o = 0.3 \ a_m \ (\varphi_o)^{-1} \qquad (5b)$$

In average, the φ_o-values is equal about 0.20-0.25. In this cases, the a_o-value varies between 0.5 m^3/mh (in tight structures) and higher than 1.5-2.0 m^3/mh at 1 daPa (in tested houses).
Equations (2,3,4) and (5) can be the basis for deciding the limit of tightening and also forthe choise of ventilation systems.

Buildings are divided according to the ratio of gross enclosure area to the houses as whole volume, e.g. $D = A_z/V$ in m^{-1}. The average air flow coefficients are function of aerodynamic conditions, i.e. the pressure differences characteristic of different buildings their location in the terrain, etc. The data shown on Fig.6 are representative for free-standing buildings [10]. Asshown from this figure, the most characteristic for winter season can be made for the external temperature $t_e = 0^oC$, and vind velocity w = 5 m/s [4,7,9,10]. The results of large number calculations served for construction of the nomograph for definition the limit of tightening and also the type of ventilation system to apply. This nomograph is presented on Fig.7. According to the ventilation requirements, the minimum ventilation rate must be about 0.5 per hour; this air change rate corresponds with the ventilation rate for buildings as a whole, even for the periodical increases of exhaust air flow during cooking and bathroom occupancy [1,3,7]. As shown from Fig.7, in the part of buildings the air change rate is lower than the minimum ventilation rate (n_{min}). Therefore, in these buildings, e.g. if the ratio D is lower than 0.6 m^{-1}, the controlled ventilation systems must be installed. The natural ventilation can be recommended if the ratio D is higher than 0.6 m^{-1} (see on the left part of Fig.7). In these buildings, the average air flow coefficient is about 0.8 m^3/m^2h at 1 daPa. For typical percentage of windows area to the gross of enclosure, these coefficients per 'm' of the total lenghth of gaps in windows are about 1.6-2.0 m^3/mh at 1 daPa.
The detail requirements for houses with the natural ventilation are shown in the lower-left side of Fig.7.

The comparison of measured and calculated a_o-values and the total ventilation rates prove that the natural ventilation may be applied in all single - family houses and the part of multi - family buildings (the maximum height - 3 floor levels).

CONCLUSION

1. The air leakage rates through the external walls of eighty dwelling houses with the natural ventilation varied considerably with values of 2.0 to 3.5 m^3/m^2h at the pressure difference is about 5 daPa. This values corresponds with the total ventilation rates about 0.4 per hour (in small houses) or 2.0 per hour (in multi - family blocks). In this cases, the fraction of the ventilation heat losses varies between 15-20% for single - family houses and even 50% for multi - family buildings.

2. The agreement between results of measurements and calculations gives confidence that the simple method may provide as means of estimating house infiltration rate. This method single-cell model can be helpful for the determination of tightening of building structures. In Poland the standard on airtightness of buildings is in preparation. This paper is an attempt to form some background general decisions.

3. The research works will be continue into next area: measurements of air exchange in various rooms in an airtight dwelling houses, measurements and calculations of air flows between internal rooms and in buildings with the mechanical systems, arrangement of supply air intake through the building envelope, etc.

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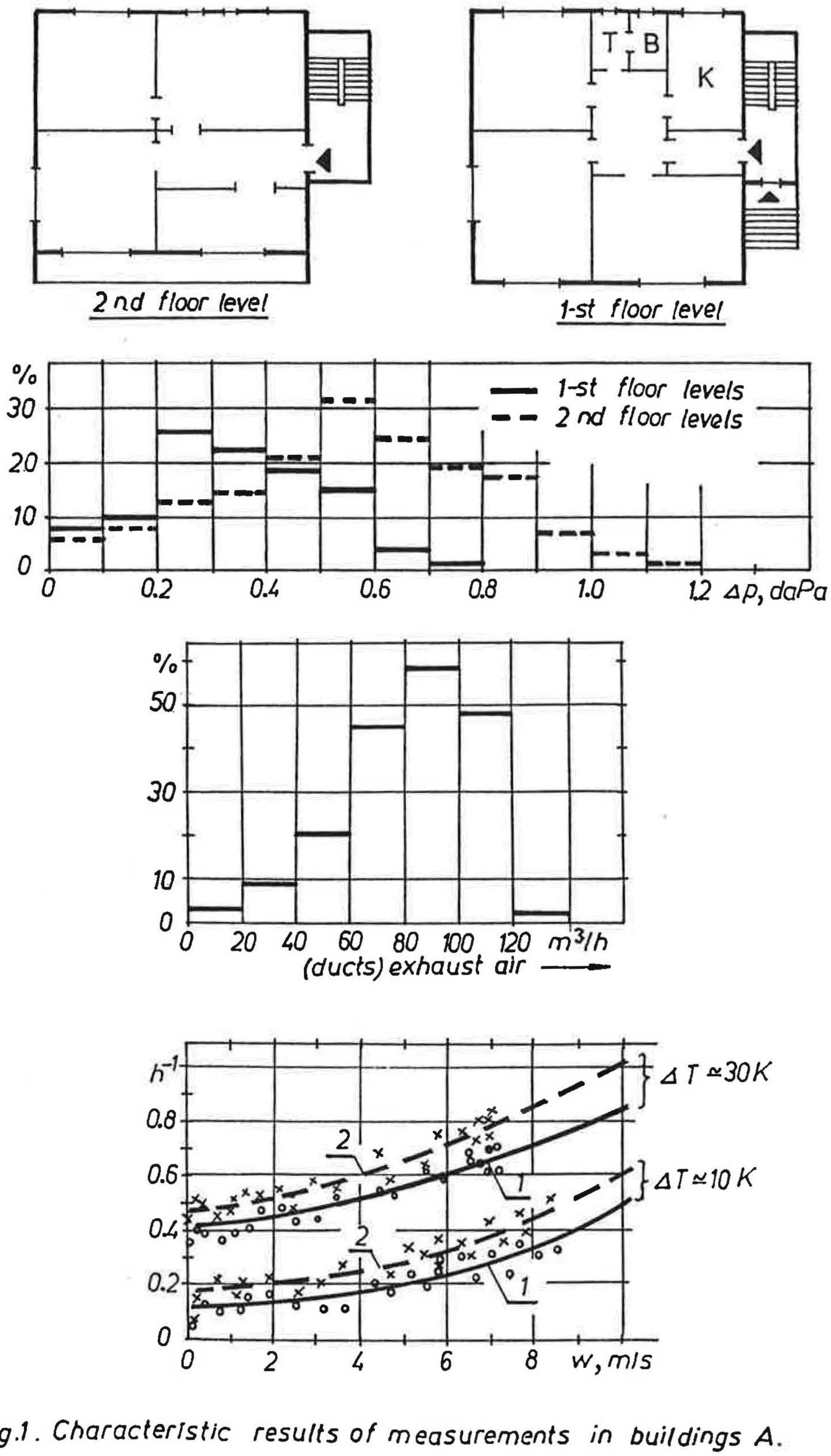

Fig.1. Characteristic results of measurements in buildings A.

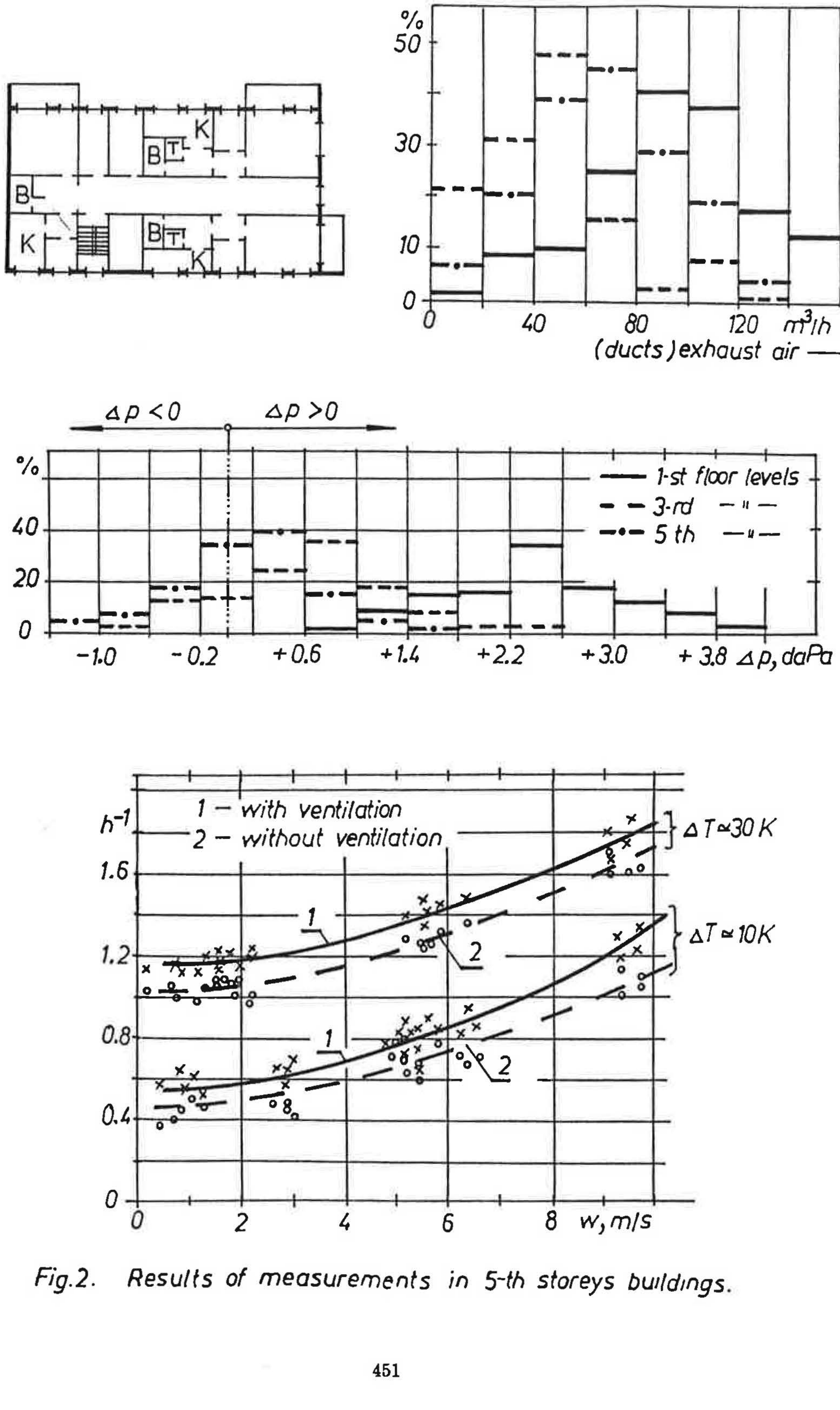

Fig.2. Results of measurements in 5-th storeys buildings.

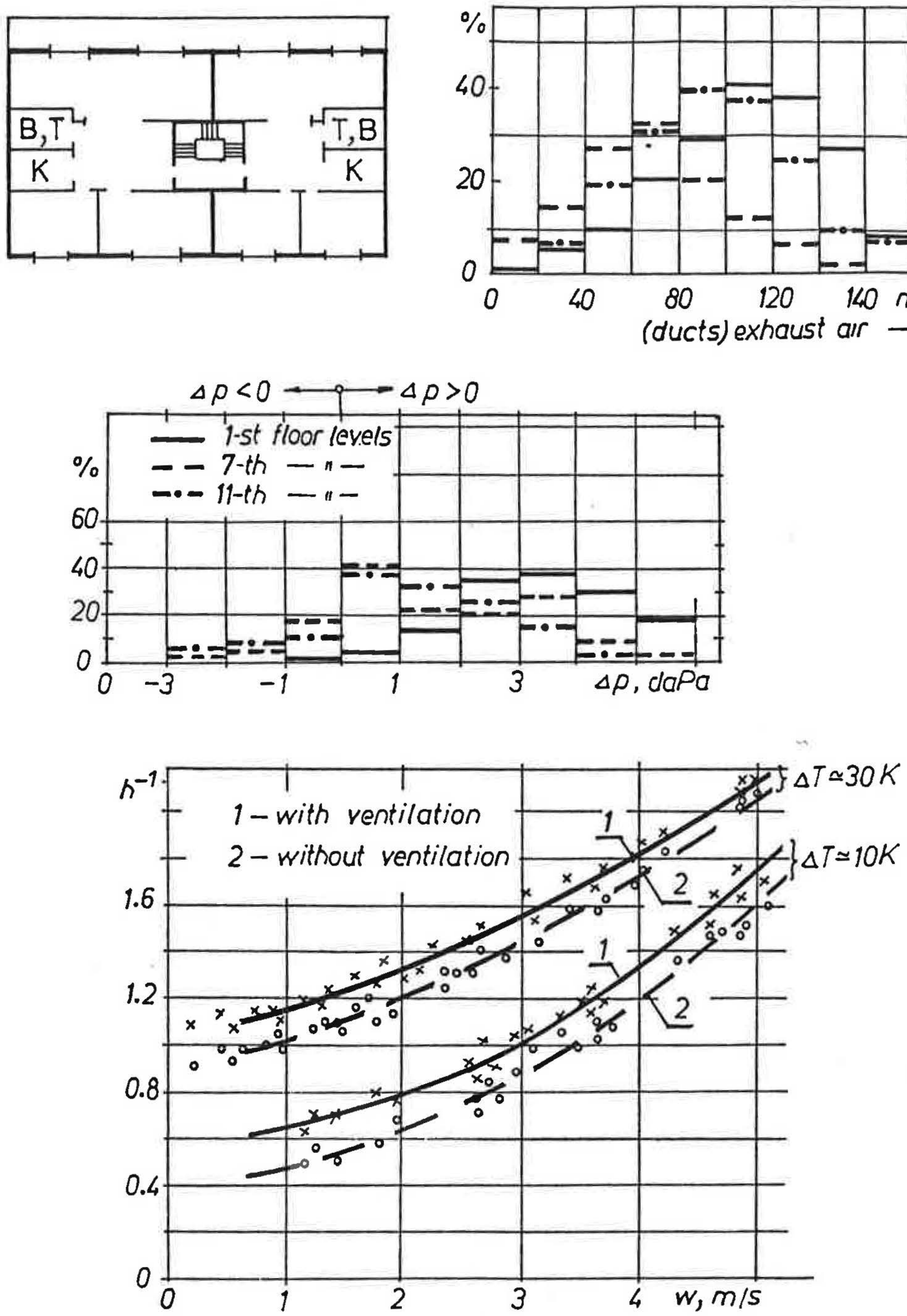

Fig.3. Results of measurements in 11-th storeys buildings.

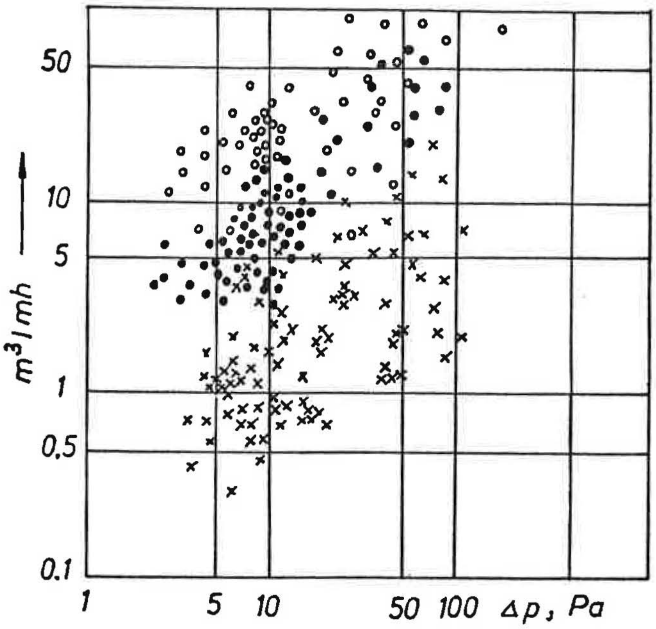

Fig.4.

Comparison of air leakage rates through windows (•) doors (∘) and floor wall joints (×) in examined buildings.

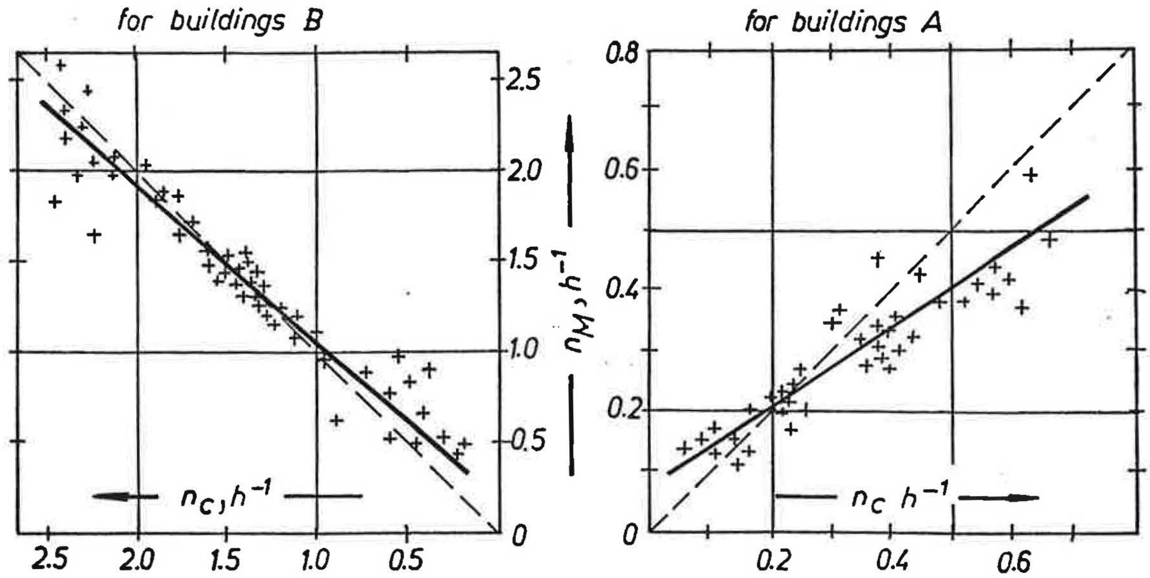

Fig.5. Comparison of measured (n_M) and calculated (n_c) air change rate in two types of tested buildings.

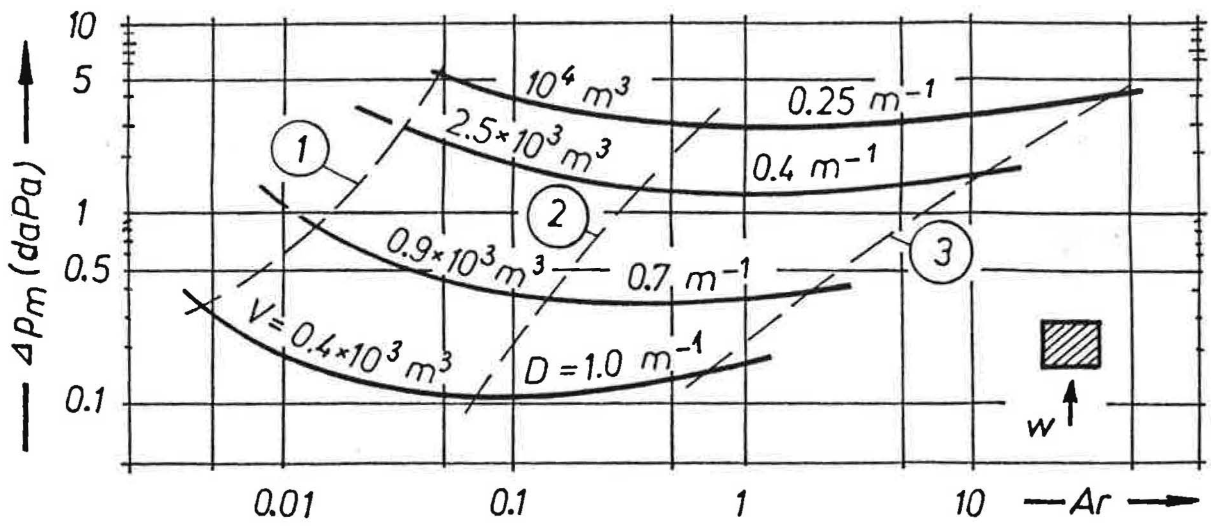

Fig.6. Relation between the average pressure differences and versus the Archimedes number.

1 – t_e = +10°C , w = 10 m/s
2 – 0°C, 5 m/s
3 – –20°C, 1 m/s

} t_i = + 20°C

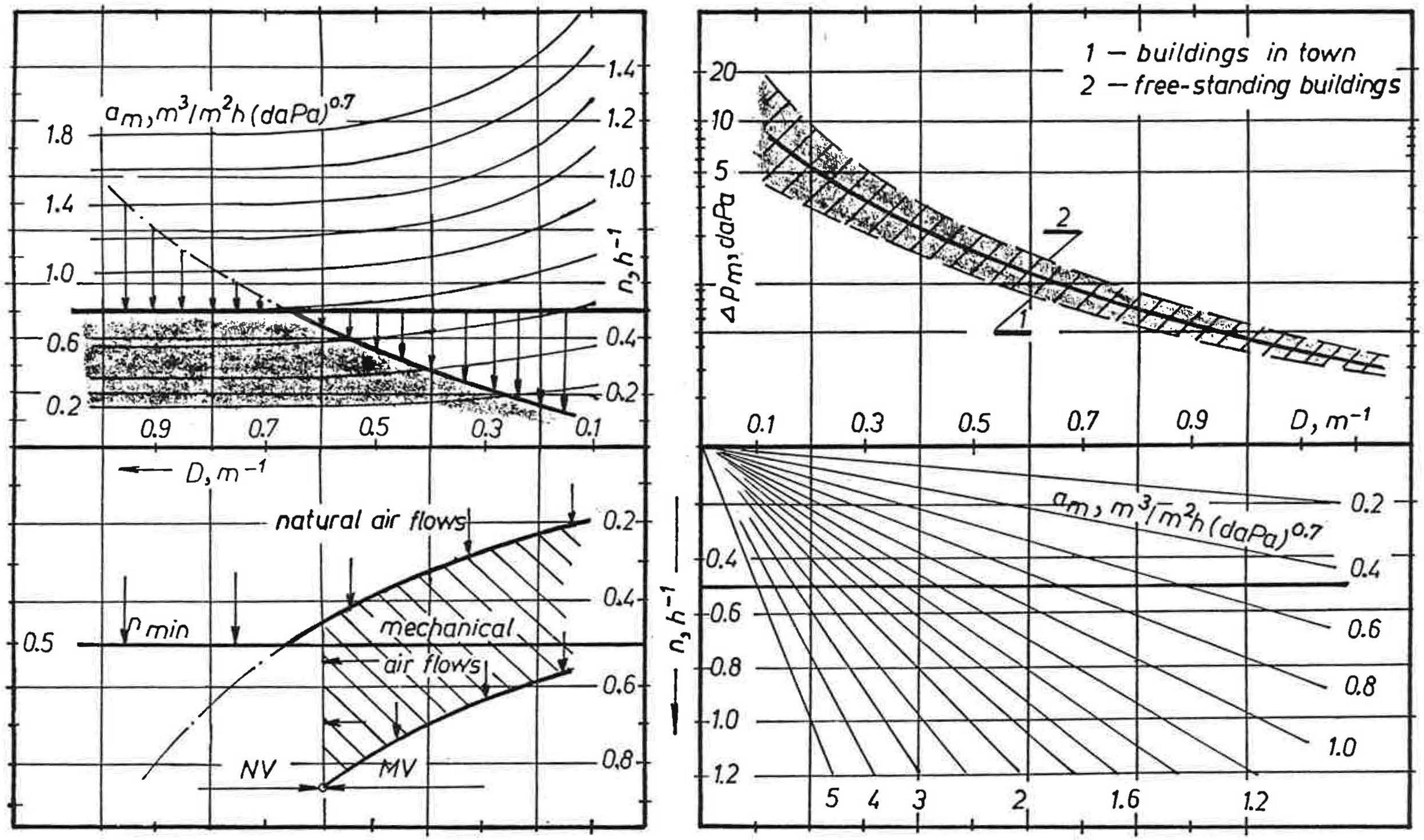

Fig. 7. Nomograph for the choise of ventilation systems and the limit of tightening in different buildings.