

697.135:72.011.27

Air exchange in multi-storey buildings

by

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Ciep. Orgrz. Went. March 1970, p. 81-85.

H.V.R.A. Translation No. 216.

Air changes in multi-storey buildings depend on many factors, among others the effect of wind, the gravity pressure of wind in the building, the method of ventilation, the air infiltration through inner and outer obstructions (partitions) and the lay-out of rooms in the building (the lay-out of staircases, lifts, doors etc.). The effect of each of these factors is more important in multi-storey buildings than in low or medium height ones. Generally speaking air infiltrates into a building through cracks of badly fitted windows, entry doors and pores and capillaries of outer walls. During the passage the air heats up to the temperature of the building. The movement of halls (corridors), as well as by leakage through the inner partitions. The air finds its way outside through extraction fans and cracks in partitions of the upper storeys situated downstream of the prevailing wind. The points and magnitude of air infiltration change during the heating season, which makes it difficult at any given time to adjust the output of the heating system to meet the requirements of individual rooms.

The flow of air through a partition depends on the pressure difference across it. To calculate the various pressures outside and inside the building and also the air flow through walls and partitions, it is essential to consider the dimensions of the building, shape, infiltration coefficients of all elements of the building, aerodynamic coefficients, wind velocity, outside and inside temperatures. The problem reduces itself to the solution of a set of equations dealing with the air balance for individual rooms. These equations will contain non-linear relationships between air flow and pressure drop across windows, doors, fan ducts etc., and would be tedious to solve. It should be possible to solve these equations by mechanical calculating methods (electrical or hydraulic analogy, electronic machines), but an approximate calculation which would also take into account the inside and outside temperatures, wind velocity, the lay-out of the ventilation ducts, construction of windows, doors and outer walls can be done more easily. It would still require a fair amount of work. The various factors affecting the air balance in a building will now be considered, i.e.

- air infiltration through walls, windows and doors,
- air flow through gravity ventilation ducts,
- the pressure pattern on the outside walls of the building,
- "chimney draught" in the staircase.

#### Air infiltration through walls, windows and doors

If there is a pressure difference between the air outside and inside the building, air will infiltrate into the building or exfiltrate from the building should the inside pressure be higher than the outside pressure. The permeability measure of any obstruction (partition) to the flow of air is the coefficient  $E_F$ , numerically equal to the quantity of air ( $m^3$ ) passing through one  $m^2$  in one hour at a pressure difference of 1 mm  $H_2O$  (1 kg/ $m^2$ ). The coefficient  $E_F$  has therefore the following dimension:

$$\frac{m^3}{m^2 h \frac{kG}{m^2}} \longleftrightarrow \frac{m^3}{m^2 h mm H_2O}$$

and numerically its values are:

- for a 2½ brick thick wall plastered on one side  
 $E_F = 0.058 \text{ m}^3/\text{m}^2\text{h mmH}_2\text{O}$  ;
- for a 9 cm thick concrete slab, plastered on one side,  $E_F = 0.021 \text{ m}^3/\text{m}^2\text{h mm H}_2\text{O}$ ;
- for windows,  $E_F = 3 \div 12 \text{ m}^3/\text{m}^2\text{h mmH}_2\text{O}$ ,
- for doors,  $E_F = 40 \text{ m}^3/\text{m}^2\text{h mmH}_2\text{O}$ ,

It can therefore be stated that the influx of air to the interior as well as the eflux to the outside of the building takes place mainly through cracks of poorly fitted doors and windows.

The quantity of air passing through these cracks can be calculated from the following empirical relationship:

$$V = \sqrt{E\ell\Delta p}^{2/3} \text{ m}^3/\text{h} \quad (1)$$

where  $\ell$  = Length of crack in windows or doors, m.

$E$  & permeability coefficient of doors and windows related to a crack of 1 m, length,  $\text{m}^3/\text{m}^2\text{h mm H}_2\text{O}$

$\Delta p$  = pressure difference across an element of window or door, mm H<sub>2</sub>O

#### AIR FLOW THROUGH GRAVITY VENTILATION DUCT

The total pressure loss along the gravity ventilation duct, which is most frequently made in concrete, but sometimes built of bricks, is defined as:

$$H = \Sigma (R\ell + Z) \text{ kG/m}^2 \quad (2)$$

where  $R$  = unit pressure drop,  $\text{kG/m}^2$

$\ell$  = length of duct, m.

$R\ell$  = linear pressure drop,  $\text{kG/m}^2$

$Z$  = local pressure drop caused by obstructions of a particular part,  $\text{kG/m}^2$

The air flow in the gravity ventilation duct is laminar or turbulent in the transitional region.

Table 1. gives (as an example) results of calculations based on an equivalent diameter of ventilation duct of  $d_h = 0.14 \text{ m}$ . Pressure losses have been calculated for assumed duct lengths from 2 to 27m and  $\Sigma\zeta = 5.4$  ( $\zeta$  grate = 3.0; change of direction at grate = 1.4 and  $\zeta = 1.0$ ) at air flow rates in the duct from 5 to 300  $\text{m}^3/\text{h}$ . The numerator shows unit losses, and the denominator total losses. Similar calculations have been carried out for four most frequently encountered cross sections of ventilation ducts:

- a)  $F = 0,14 \cdot 0,14 \text{ m}; d_h = 0,14 \text{ m}$
- b)  $F = 0,14 \cdot 0,21 \text{ m}; d_h = 0,168 \text{ m}$
- c)  $F = 0,21 \cdot 0,21 \text{ m}; d_h = 0,21 \text{ m}$
- d)  $F = 0,21 \cdot 0,27 \text{ m}; d_h = 0,237 \text{ m}$

Figure 1 & 2 give curves illustrating the results of calculations based on  $d_h = 0.14 \text{ m}$  and  $d_h = 0.168 \text{ m}$ .

These curves enable the relationship between pressure loss and the quantity of air passing through a duct of a given cross section and length to be found.

This relationship has the form of

$$H = a \cdot V^n \text{ kG/m}^2 \quad (3)$$

where  $H$  = total pressure loss,  $\text{kg/m}^2$

$V$  = air flow through the duct,  $\text{m}^3/\text{h}$

$a, n$  = constants specific of the type and length of a given duct.

From Figures 1 and 2 it can be seen that for turbulent flow in the transitional region, the total pressure loss  $H$  is proportional to the square of the air flow  $V$  ( $n = 2$ ) and in the laminar flow region the values for  $n$  are equal for corresponding duct lengths  $d_h = 0.14\text{m}$  and  $d_h = 0.168\text{m}$ .

#### PRESSURE PATTERN ON THE OUTSIDE WALLS OF THE BUILDING

The pressure at any given point on the surface of an outer wall of a building is the sum of the changing atmospheric pressure and that caused by the wind. In the case of tall building the changes in atmospheric pressure which depend on the outside temperature, must not be ignored. These changes depend on the height of the position under consideration. The pressure increment effected by the action of the wind (as a result of the change of some of the kinetic energy to static pressure energy) is not the same for the whole surface of the wall. This increment, which depends in the first place, on the wind direction, is different for individual points of the wall surface.

The fact that the wind velocity differs across the wind stream explains the change of that increment. The real increase in pressure effected by wind action is expressed by the general formula:

$$P_{stw} = C \frac{v_w^3}{2g} \text{ kG/m}^2 \quad (4)$$

where C = aerodynamic coefficient

Vw = velocity of wind flow (with no obstacles in its path), m/s.

The aerodynamic coefficient C determines that fraction of the kinetic energy of the wind that has changed into energy of static pressure (upstream), alternately, it gives the fraction of the static pressure of the air flow which was used for increasing the wind velocity (downstream). An accurate calculation of the aerodynamic coefficients for a given shape and size of building is only possible as a result of tests on a model in an aerodynamic (wind) tunnel. These coefficients will differ for different directions of wind acting on the building.

The change of wind velocity in relation to height of building, simultaneously, the pressure change effected by wind action) takes place at the height of 10 to 15 m from the ground.

This change according to investigations carried out by Hellman on models is defined by the relationship:

$$\frac{V_{w1sr}}{V_{w2sr}} = \left( \frac{h_1}{h_2} \right)^{1/5} \quad (5)$$

where:  $V_{w1sr}$  = mean wind velocity up to the height of 10m above ground, m/s

$V_{w2sr}$  = as above, but at height  $h_2$   
above ground, m/s

$h_1$  = height, up to which a constant wind velocity can be assumed, m.

$h_2$  = level under consideration above ground, but at height exceeding 10m.

The maximum wind velocity can be defined on the basis of the mean velocity for a given wind direction according to the Robitzsch relationship

$$V_w \text{ max} = 1.9 V_{wsr}. \quad (6)$$

Up to the height of 10m from the ground a constant wind velocity can be assumed (fixed for the particular wind region on assumption that the building in question is not sheltered). Above 10m the wind velocity at various heights is defined according to formula (5) see Figure 3.

The pressure change caused by the wind acting on the front wall (upstream) depends also on the shape of the building washed by the air stream. The static pressure distribution along the vertical cross section of the building, when the air flow is at right angle to the front of the building, no account being taken of wind velocity increase due to height, is given in Figure 4. Model investigations have shown that the static pressure differs not only along the height of the front wall, but also along its length. Therefore in multi-storey buildings it is possible to divide the surface horizontally into two principal zones.

1) The middle part of the building, 2) The extremes of the building.

The size of these zones can only be determined from model work and observation of the velocity distribution (of static pressures) on front walls (upstream) taking into account the different (typical directions are perpendicular and 45° to the front wall). They can be defined for close enough

values of static pressures.

Figure 5 illustrates such a division into zones of a building, whose model has been investigated in a wind tunnel. It can be assumed that on the down-stream side the underpressure is constant along the total height of the wall of the building.

#### 'Chimney draught' in the staircase

When the ambient temperature is higher than that inside the building the air from the lower part of the staircase moves upwards as a result of the density difference between the outside air and that in the staircase. The force of the draught depends also on the height of the staircase and is expressed by the following formula:

$$H = h_k (\gamma_z - \gamma_w), \text{ kG/m}^2 \quad (7)$$

where:  $h_k$  = height of staircase, m.

$\gamma_z, \gamma_w$  = specific gravity of outdoor air and that filling the staircase respectively,  $\text{kG/m}^3$ .

This phenomenon taking place in tall buildings has a serious influence on air movements inside the building and must not be ignored when considering its air characteristics.

#### Calculation model (mathematical model) for carrying out an air balance for a building with gravity ventilation ducts.

In the analytical method of calculating the air change in a building, the ambient temperature is assumed to be equal to that of the average winter temperature for the purpose of determining the wind velocity. This method is used as a basis for calculating the heat requirements to be met by the heating plant. If the object is to assess the gravity ventilation requirements, then it is assumed that the ambient temperature is  $5^\circ\text{C}$  and an average wind velocity corresponding to this temperature is taken. The calculations for both the former and latter case must be made for several characteristic wind directions. Knowing the aerodynamic coefficient for the wall in question and the velocity distribution along the height of the building it is possible to find in a particular zone the increase in pressure caused by the action of the wind. A simplified model for an air balance for any room in a building is represented in Figure. 6. In drawing up an air balance for a room (or a number of rooms) chosen along the height or width of the building the following designations and assumptions have been made:

Atmospheric pressure at the exit of the gravity ventilation duct is assumed to be

$$p_a = 0;$$

pressure at the highest point of the staircase (unknown quantity)  $\text{kG/m}^2$ ;  
for the sake of simplicity, it is assumed that inside the room (apartment) in question the pressure is constant (at that level) and it is  $p_{xi}$  (unknown);

$h_o$  = distance from the assumed data level  $p_a = 0$  to the middle of the window openings of the considered apartment, m;  $h_{ok}^a$  as above, but to the middle of the windows openings of the staircase, m;  $h_{idk}$ , as above, but to the middle of the entrance door to the staircase, m.  
 $h_{id}$  = distance from the level, where there is an unknown pressure  $p_k$  (normally equal to  $p_a = 0$ ) to the middle of the door opening into the staircase, m;

$h_{ik}$  = distance from data level to the centre of inlet to the duct, m. In addition, it is assumed that air infiltrates into the building or finds its way out from the building through badly fitted windows, doors and by means of the gravity ventilation duct, whereas partitions between any apartments are impermeable to air passage.

Based on these assumptions the quantity of air that flows into the building through badly fitted windows is given thus:

$$V_1 = \Sigma (IE)_o (p_w + h_{io} \gamma_z - p_{xi})^{0.67} \text{ m}^3/\text{h} \quad (8)$$

where  $\Sigma (IE)_o$  = quantity of air passing through window cracks under pressure difference  $\Delta p = 1 \text{ kg/m}^2$ ,  $\text{m}^3$ ;  
 $p_w$  = pressure resulting from wind action at the considered window opening,  $\text{kg/m}^2$   
 $\gamma_z$  = specific gravity of outside air,  $\text{kg/m}^3$ .

The quantity of air passing through badly fitted door openings into the staircase is given by the following relationship:

$$V_2 = \Sigma (IE)_d (p_k + h_{id} \gamma_w - p_{xi})^{0.67} \text{ m}^3/\text{h} \quad (9)$$

where:  $\Sigma (IE)_d$  is as above, but for the doors;  
 $\gamma_w$  = specific gravity of air in the staircase,  $\text{kg/m}^3$

Knowing the characteristics of the given ventilation duct, the quantity of air passing through it can be calculated from the following formula:

$$V_3 = a_i (p_{xi}' - h_{ik} \gamma_w + p_w)^n \text{ m}^3/\text{h} \quad (10)$$

where  $a_i$  and  $n$  are constants for the given type and length of duct used as an example in the nomograms (Fig.1 and 2)

$p_w$  = pressure at the outlet from the duct effected by wind action.

Let  $p_{xi}' = p_{xi} - h_i \gamma_w$  and assuming

$$h_{io} = h_{id}$$

then the balance of incoming and outgoing air from the apartment will be

$$\Sigma (IE)_o (p_w + h_i (\gamma_z - \gamma_w) - p_{xi}')^{0.67} + \Sigma (IE)_d (p_k - p_{xi}')^{0.67} = a_i (p_{xi}' + p_w)^n \text{ m}^3/\text{h} \quad (11)$$

Similar equations for air balance must be written for all apartments adjacent to the staircase.

The quantity of air passing through (into or out from) the cracks because of leakage of windows and entrance door  $p$  to the staircase is

$$V_4 = \Sigma (IE)_{ok,dk} [p_k + h_{iok,dk} \gamma_w - (h_{iok,dk} \gamma_z + p_w)]^{0.67} \text{ m}^3/\text{h} \quad (12)$$

$$V_4 = \Sigma (IE)_{ok,dk} [p_k - (h_{iok,dk} \Delta \gamma + p_w)]^{0.67} \text{ m}^3/\text{h} \quad (13)$$

The solution of equation (11) for  $p_{xi}$ ,  $p_k$  and equation (13) for  $p_k$  will enable us to obtain an account of the air change process taking place in the building.

### Effects of uncontrolled air movements in a tall building

The solution of an air balance for a building with gravity ventilation ducts or the knowledge of the functioning of various ventilation systems (with culverts through 2, 3 or 5 storeys, duct in the form of a shaft with side openings of different cross sections) enables the following observations to be made:

- 1) In the staircase there is an air movement from the lower storeys to the upper ones accompanied by a spread of bad smells in the whole building.
- 2) Large quantities of air infiltrate from outside into the lower storeys when the ambient temperature is low.
- 3) It is impossible to secure adequate ventilation for rooms apartments on the upper storeys; observations indicate that already at  $t_z = 5^\circ\text{C}$  and the absence of wind, the currently applied ventilation systems do not provide the required air quantities. These observations point to the necessity of finding new solutions to the problem of gravity ventilation systems. The first to make observations of the steadiness of operation of several gravity ventilation systems was W.E.Konstantinova, who did it for the following ventilation scheme of a 16 storey building:
  - a) A ventilation system with separate ventilation ducts converging into one duct in the attic.
  - b) A duct system with passages through 2 and 5 storeys.
  - c) A single duct system with side grids of different cross section on the various storeys, designed for even extraction from each storey.

The investigation was carried out under conditions of varying pressure in the apartments caused by wind action, opening of doors, windows, vents etc. Most frequently the indoor pressure changes as a result of opening windows when it becomes equal to that outside the building. This local pressure rise may effect the operation of the ducts serving the apartment in question and may even cause a reversal of draught.

Investigations have shown that the most even distribution of air on the various storeys is achieved by a single duct system with side grids of varying cross section, and also a system with separate extraction ducts. This system has the least cross sectional area of ducting and therefore is most economical.

### Conclusions

The generally accepted views on the intensity of air infiltration into tall buildings (to lower and upper parts) are not borne out by calculations. As a result of the 'chimney draught' effect large volumes of air from outside pass into the lower storeys, which increases the demand for heat, and large volumes of warm air flow to the upper storeys.



Of great importance is the proper design of the extraction gravity ventilation system. In the absence of an adequate steadiness (balance) of duct operation a flow of air may take place from the lower storeys to the upper ones through the staircase and also a decrease or even a reversal of draught in the duct.

Table I

Pressure losses in the gravity ventilation duct for air flows from 5 to 300m<sup>3</sup>/h; length of duct from 2 to 27m at d<sub>h</sub> = 0.14m.

l	Rl <sub>5</sub>	Rl <sub>10</sub>	Rl <sub>20</sub>	Rl <sub>40</sub>	Rl <sub>90</sub>	Rl <sub>150</sub>	Rl <sub>250</sub>	Rl <sub>300</sub> <sup>*)</sup>
2,0	0,00044	0,00088	0,00174	0,0124	0,0570	0,150	0,404	0,56
	0,00206	0,00748	0,0277	0,1184	0,597	1,59	4,654	6,46
12,0	0,0028	0,0052	0,0106	0,074	0,34	0,9	2,44	3,36
	0,0042	0,0118	0,0366	0,178	0,88	2,34	6,69	9,26
19,5	0,0041	0,0084	0,017	0,12	0,56	1,46	3,95	5,5
	0,0057	0,0150	0,043	0,224	1,10	2,90	8,20	11,4
27,0	0,006	0,0116	0,023	0,157	0,78	2,02	5,5	7,6
	0,0076	0,0182	0,049	0,261	1,32	3,46	9,75	13,5
Z	0,0016	0,0066	0,026	0,104	0,54	1,44	4,25	5,9

\*) Liczba w indeksie dolnym oznacza wydatek powietrza.

The number at the foot of Rl denominates air flow.

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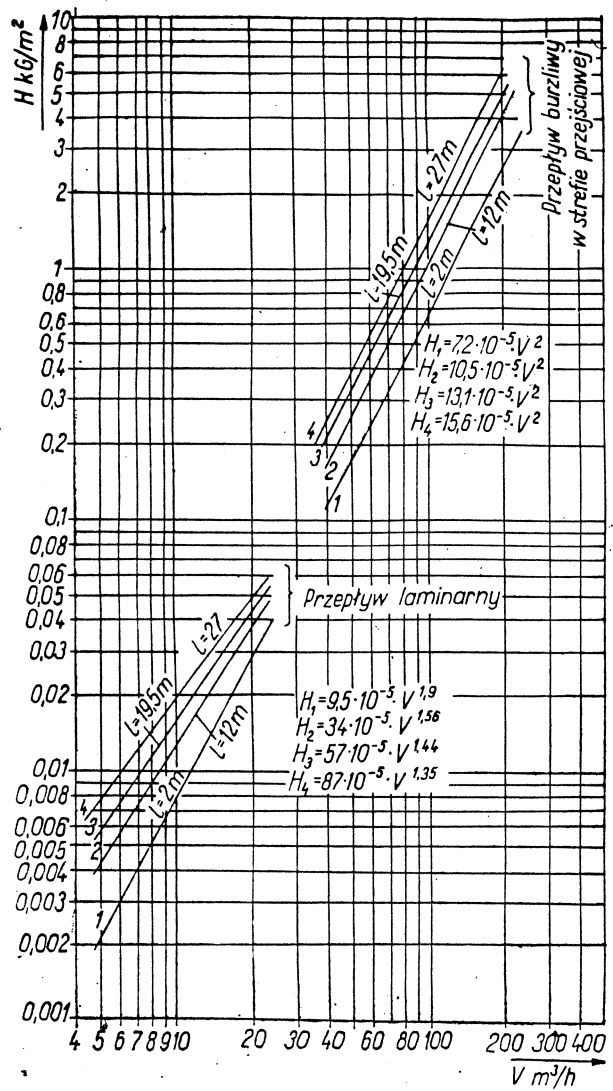


Fig.1. Nomogram to determine the total pressure loss  $H$  w air flow  $V$  for a concrete channel of rectangular cross section  $F = 0.14m \times 0.14m$  ( $d_h = 0.14m$ ), length of channel  $l = 2$  to  $h_{27}m$ .

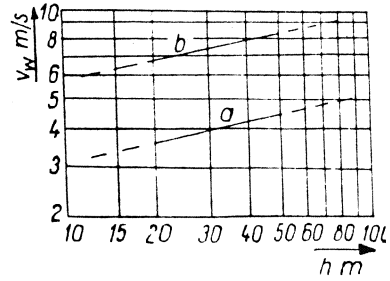


Fig.3. Wind velocities at different levels above ground (average velocity on ground  $v_{sr} = 3.1m/s$ ): a) for average wind velocity, b) for extreme velocities in relation to the average velocity

Turbulent flow in transitional region.

Laminar flow.

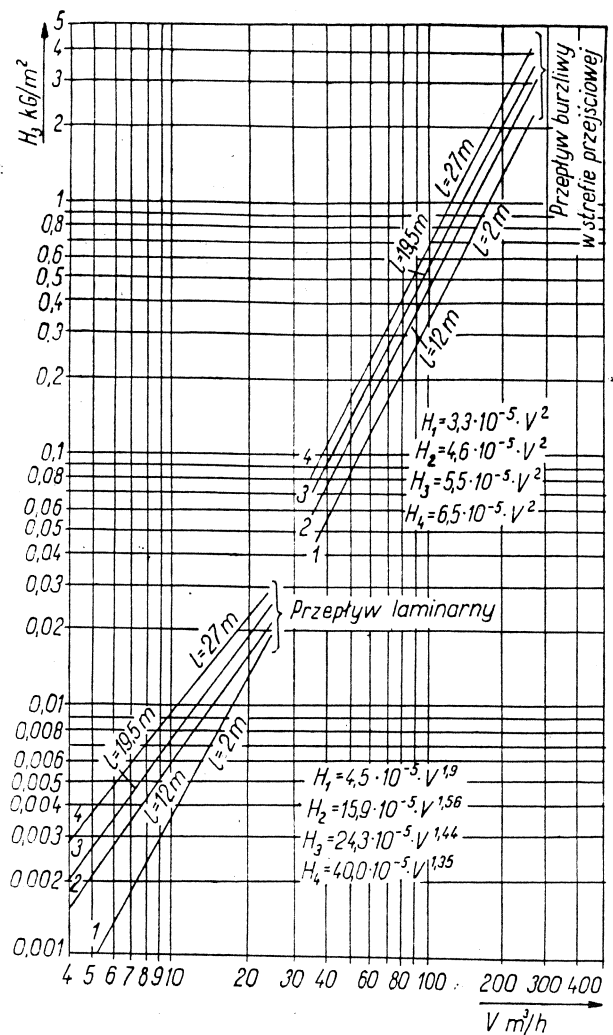


Fig.2. Nomogram to determine the total pressure loss  $H$  w, air flow  $V$  for a concrete channel of rectangular cross section  $F = 0.14m \cdot 0.21m$  ( $d_h = 0.168m$ ), length of channel  $l = 2$  to  $27m$ .

Turbulent flow in transitional region.

Laminar flow.

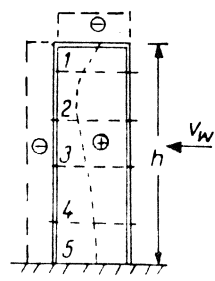


Fig.4. Vertical cross section through the middle of the building with the wind direction at right angles to the front. No account is taken of the wind velocity increase with height above ground; "+" denotes pressure caused by wind action, "-" denotes underpressure through wind action 1,2,3,4,5 are zones into which the building has been divided.

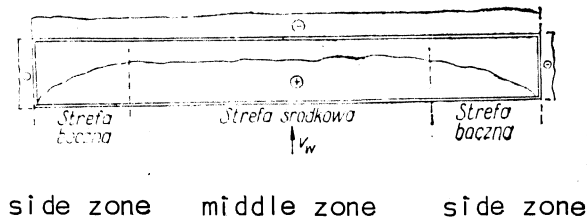


Fig.5. Pressure distribution when wind flow is at right angle to the front of the building. "+" denotes pressure caused by wind action "-", underpressure caused by wind action.

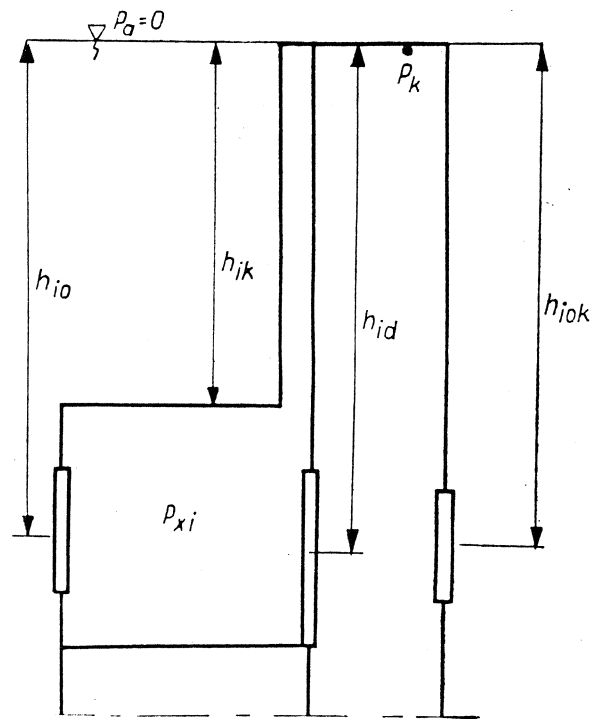


Fig.6. Calculation (mathematical) model for an apartment (or a number of apartments) with gravity ventilation extraction duct.