PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

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AIR CHANGE IN FLATS WITH NATURAL VENTILATION: MEASUREMENTS AND CALCULATIONS

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SYNOPSIS

The air change rate in existing, older blocks of flats having natural ventilation has been measured by the tracer gas method. Measurements were made in the buildings in as-found condition. The average air infiltration rate was 0.26 air changes/h (with the ventilation ducs closed), with an overall ventilation rate of 0.47 air changes/h. The average overall ventilation rate is very close to that recommended on the basis of health requirements, although values both above and below this are encountered in many flats.

A comparison has been made between measured air change rates and calculated air change rates using the JK-CIRCUS computer program. The results show that airtightness of wall and windows in older flats is equivalent to an average n_{50}-value of 1.5 air changes/h. n_{50} is the air change rate at a differential pressure of 50 Pa between interior and exterior. The building regulations specify an n_{50} air change rate of less than 1.0 air changes/h in new blocks of flats.

Calculations using the JK-CIRCUS program show that, for a flat having a natural ventilation system, improving the airtightness of the windows will result in a maximum reduction in air change rate of 0.1 air changes/h for an external wind speed range of 2-8 m/s.

LIST OF SYMBOLS

A	Admittance	m^3/sPa
a	Flow rate coefficient	m^3/sm^2Pa^b
B_o	Fluid permeability coefficient	m^2
b	Flow exponent	–
h	Chimney height	m
n	Air change rate	h^{-1}
p	Pressure	Pa
q	Air flow rate	m^3/s
u	Wind speed	m/s
ε	Surface roughness	m
η	Dynamic viscosity	Ns/m^2
θ	Temperature	K
λ	Friction factor	–
ν	Kinematic viscosity	m^2/s
ξ	Loss factor	–
ρ	Density	kg/m^3
μ	Form factor (wind)	–

1. AIR CHANGE RATE MEASUREMENTS - VENTILATION IN FLATS

A number of Swedish blocks of flats, built between 1860 and 1960, have been investigated in respect of various behaviourial characteristics, including air change rates. The measurements were made in as-found condition in 29 flats having natural ventilation.

1.1 Measurement procedure

The air change rate of a flat indicates how many times the air inside the flat is replaced by outdoor air per unit of time.

Air change rate measurements were made using the tracer gas method, involving the use of a gas analyzer which measures the concentration of laughing gas (N_2O) discharged inside the flat. The rate at which the gas concentration declines depends on the ventilation rate: the higher the ventilation rate, the more rapidly the gas concentration declines.

The measurement period for each flat has normally been of the order of 4-8 hours. Wind speed and indoor/outdoor temperature difference play a part in determining the ventilation rate, and have therefore been noted in connection with each set of measurements. The measurements have mainly been made during the winter, when the temperature difference between the indoor and outdoor air was greatest.

The air change rate has been investigated for two different cases: infiltration and normal ventilation. Infiltration (uncontrolled ventilation) is represented by the condition encountered when all ventilation fittings are sealed so that the only ventilation resulting is that caused by air leaks through the building envelope. This is, of course, an abnormal condition, and it is not possible simply to add the infiltration rate to the intended ventilation rate. However, the measurements do provide an indication of the airtightness of the building envelope. Normal ventilation conditions are those when no ventilation fittings are sealed, but are opened as they normally should be.

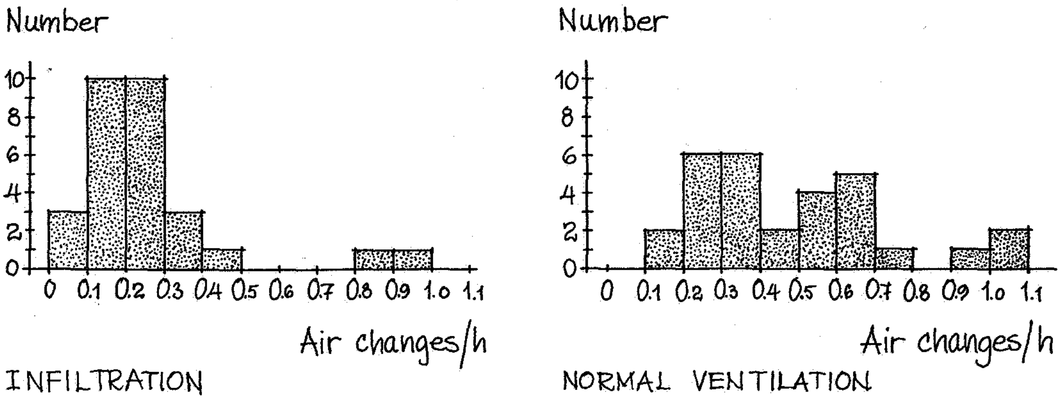
1.2 Measurement results

The results of the measurements are presented in Table 1. The table shows the as-measured values, i.e. no corrections have been applied for wind or temperature differences at the time. The values have been grouped in accordance with the ages of the buildings.

Table 1 As-measured values of ventilation air change rates in flats in Malmö, Eksjö and Gävle, and having natural ventilation.

Flat no.	Year of building	Wind speed, m/s	Wind direction	Temperature difference, indoor/ outdoor, K	Infiltration air changes/h	Normal ventilation, air changes/h
1	1835	0.25- 0.75	N	21-22	0.92	1.00
2	1884	0.1 - 0.3	N-NE	20	0.23	0.29
3	1894	0 - 1.3	S	23.5	0.46	0.69
4	1897	1.6 - 2.0	SE	3	0.16	0.18
5	1898	0.3	N	24	0.87	1.00
6	1898	0.5 - 0.8	E	25	0.24	0.36
7	1898	0.1 - 3.9	W	9.5	0.26	0.30
8	1899	0.2 - 1.4	W	20-22	0.29	0.54
9	1905	1.5	E	19-23	0.36	0.35
10	1920	1.2	N	17	0.35	0.60
11	1922	1.8 - 2.6	N	15	0.15	0.24
12	1927	0.1 - 0.3	W	17.5-23	0.16	0.23
13	1927	0.4 - 1.1	W	20-25	0.38	0.55
14	1930	2.3 - 2.6	E	17	0.22	0.38
15	1934	2.2 - 3.8	SE	13	0.17	0.33
16	1934	2.3 - 2.7	S	21	0.21	0.50
17	1938	2.0 - 2.8	SE	18.5	0.27	0.47
18	1938	1.2 - 1.5	SE	13-19	0.29	0.69
19	1938	0.8	SE	26	0.16	0.53
20	1939	1.1 - 1.6	SW	22.5-23.5	0.09	0.64
21	1941	1.0 - 1.5	NE	23-24	0.23	0.92
22	1945	0.6	W	29-33	0.25	0.71
23	1946	1.0 - 1.2	SW	19-20.5	0.12	0.24
24	1946	1.6	N	19	0.12	0.21
25	1948	0.8 - 1.7	S	13-15	0.03	0.11
26	1949	2.2 - 2.4	SW	24	0.14	0.42
27	1950	1.3 - 2.0	SE	22.5-26	0.10	0.63
28	1954	0.8 - 1.2	N	20-21.5	0.06	0.35
29	1955	1.5 - 3.0	W	25-26	0.15	0.26
Mean value					0.26	0.47

The mean value of infiltration is 0.26 air changes/h, while that of normal ventilation is 0.47 air changes/h. This mean value of normal ventilation is quite close to the value recommended on the basis of health requirements (0.5 air changes/h), although there is a wide spread, and many flats have either too high or too low ventilation rates. This can also be seen clearly in Figure 1, which shows histograms of infiltration and normal ventilation air change rates.



INFILTRATION

NORMAL VENTILATION

Figure 1 Histograms of as-measured infiltration and normal ventilation air change rates for 19 flats having natural ventilation.

Table 1 shows that the air change rate varies widely from one property to another, but that the ages of the properties do not seem to have any direct effect on normal ventilation. The ages do, on the other hand, seem to have some effect on infiltration. In order to verify this, the relationship between the year of building and ventilation rate has been calculated using the method of least squares. For infiltration, the coefficient of correlation is so high (0.73) that it does seem reasonable to postulate the relationship. This relationship means that infiltration tends to increase with increasing age of buildings, while normal ventilation is not affected by the ages of the buildings, for which the coefficient of correlation is low at 0.30.

2. COMPUTER CALCULATION OF VENTILATION

The measured values of normal ventilation rates in naturally-ventilated flats have been compared with theoretical values, as calculated by computer using the JK-CIRCUS program.

2.1 The JK-CIRCUS program

This program, developed by J. Kronvall[1], performs the following calculations:

- divides the flow geometry up into finite parts - components,
- calculated the admittance, defined below of each component,
- calculates the potentials, p (Pa), at all nodes, together with the flow rates, q (m^3/s), through all components.

In the case of (air) flow problems, a component may be either:

- a pressure difference between two nodes (active component),
- a piece of permeable material (passive),
- a section of duct, in the flow direction (passive),
- a single resistance, e.g. entrance, exit or bend loss (passive),
- a potential flow $q = a \cdot \Delta p^b$ (passive).

The principle is that the air flow in the flat is described by means of a network or flow diagram, in which the various parts are referred to as components, in a manner analogous to that for an electric circuit containing a network of resistances. Each component in the flow diagram having two connections is referred to as a branch, while the connection points are referred to as nodes. Several branches can be connected to the same node.

The designations used for parts of materials or ducts are illustrated in Figure 2.

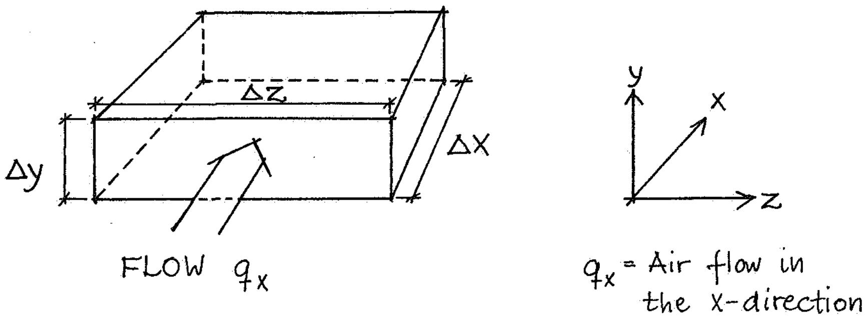


Figure 2 Definition of geometrical quantities of a component.

The computer program works with admittances. The admittance, A, of a component is defined as:

$$q_x \ (m^3/s) = A_x \ (m^3/sPa) \Delta p_x \ (Pa)$$

where Δp_x = the pressure difference across the component in the direction of flow (Pa)

According to Kronvall[1], the admittance, A, of permeable material is given by:

$$A_x = \frac{B_o}{\eta} \frac{1}{\Delta x} \Delta y \ \Delta z$$

where B_o = permeability (m^2)
η = the dynamic viscosity of air (Ns/m^2)

while, similarly, the admittance, A, of crevices and ducts is given by:

$$A_x(q) = \frac{4\Delta y^3}{\rho q_x} \frac{\Delta z^2}{\lambda \Delta x}$$

where ρ = the density of air (kg/m^3)
λ = the friction factor.

In general, the admittance of a duct depends on the flow, q, through it. With laminar flow (Reynold's number $Re < 2300$), the friction factor, λ, is inversely proportional to the flow,

$$\lambda = \frac{96}{R_e} = \frac{96 \cdot \Delta z \nu}{2q}$$

which means that the admittance is constant.

Further, the admittance, A, of a single resistance is given by:

$$A_x(q) = \frac{2\Delta y^2}{\rho q_x} \frac{\Delta z^2}{\xi}$$

where ξ = the loss factor.

The admittance, A, of the potential flows is given by:

$$A_x(\Delta p) = a\Delta y \ \Delta z \ \Delta p^{(b-1)}$$

where a = flow coefficient ($m^3/s \ m^2Pa^b$)
b = flow exponent

2.2 Prerequisites

The computer calculations were made for a naturally-ventilated flat having a floor area of 80 m². The flat has two opposing exterior walls, and is situated in the centre of multi-storey building, as shown in Figure 3. Ventilation is provided by outlets in the kitchen and in the bathroom, both connected to the main ventilation riser, the height of which is 8 m.

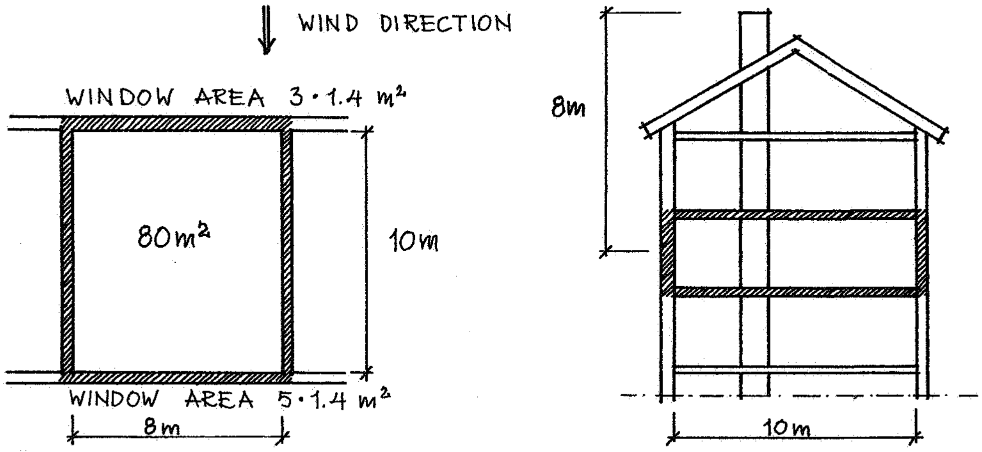


Figure 3 Dimensions and position of the flat considered in the computer calculation

The network for computer calculation of the above flat is illustrated in Figure 4:

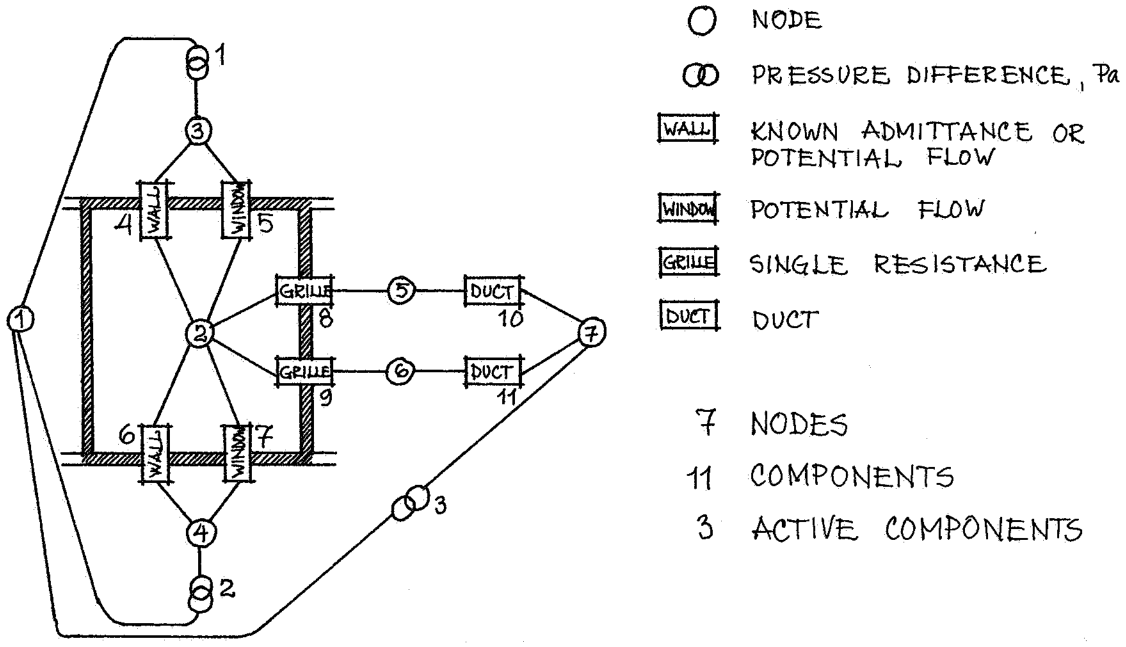


Figure 4 Computer network model of the flat shown in Figure 3.

Wind pressure has been calculated on the basis of a wind velocity of 4 m/s. Form factors of 0.7 and -0.5 respectively have been assumed for the windward and lee walls, equivalent to values assumed for wind loads in design standards. A form factor of -0.4 has been assumed for the chimney opening, as given by Liddament[2]. The wind pressure, p, can be calculated from the formula:

$$p = \mu \rho u^2/2 \quad \text{(Pa)}$$

where μ = the form factor
ρ = the density of the air (kg/m^3)
u = the wind velocity (m/s)

The difference in indoor and outdoor air temperatures results in the chimney or thermal effect, by which a difference in air pressure arises in the indoor and outdoor air. The differential pressure, Δp, can be calculated from:

$$\Delta p = 0.043\ h\ \Delta\theta \quad \text{(Pa)}$$

where h = chimney height (m)
$\Delta\theta$ = indoor/outdoor temperature difference (K)

For the purpose of the calculations, the thermal driving force has been assumed to be 8 Pa, equivalent to a temperature difference of about 23 K between the indoor and outdoor air with a chimney height of $h = 8$ m.

The facade surfaces are influenced both by wind pressure and thermal effects, while the top of the chimney is influenced only by wind pressure.

The ventilation fittings in the kitchen and bathroom are assumed to be of the grid type, and to have a size of 0.15 m x 0.15 m. The loss factor, ξ, has been assumed to be 10. The cross-sectional area of the ventilation duct from the kitchen is 0.125 m x 0.250 m, while that of the duct from the bathroom is 0.125 m x 0.125 m, both with lengths of 8 m. Surface roughness, ε, is assumed to be 0.01 m.

Computer calculations have been made for airtight windows, for which the airflow through them at a pressure difference of 50 Pa (q_{50}) is 1.7 m^3/m^{2}h, i.e. the value as assumed in the Building Regulations for new windows. However, if we consider the values of actual measurements of air leakage around older windows, Olsson-Jonsson[3], we find that few windows are actually as airtight as this. Calculations have therefore also been made for less airtight windows, for which $q_{50} = 5$ m^3/m^{2}h. The flow exponent, b, of windows having good airtightness has been given a value of 0.67, while for less airtight windows, measurements indicate that the value of b is around 0.80.

Walls, too, have been investigated in respect of their airtightness. The admittance of walls with a good level of airtightness has been assumed to be 10^{-10} m^3/sPa, i.e. around zero in practice. In the case of walls that are less airtight, there will be a potential flow through them. The flow coefficient, a, has been calculated so that the air change rate in the flat for an interior/exterior pressure difference of 50 Pa (n_{50}) is 1.5 air changes/h with poorly airtight windows as above. The flow exponent is assumed to be 0.7.

2.3 Results

Figure 5 shows the air flows into and out of the flat, and the air change rate, as calculated by the computer.

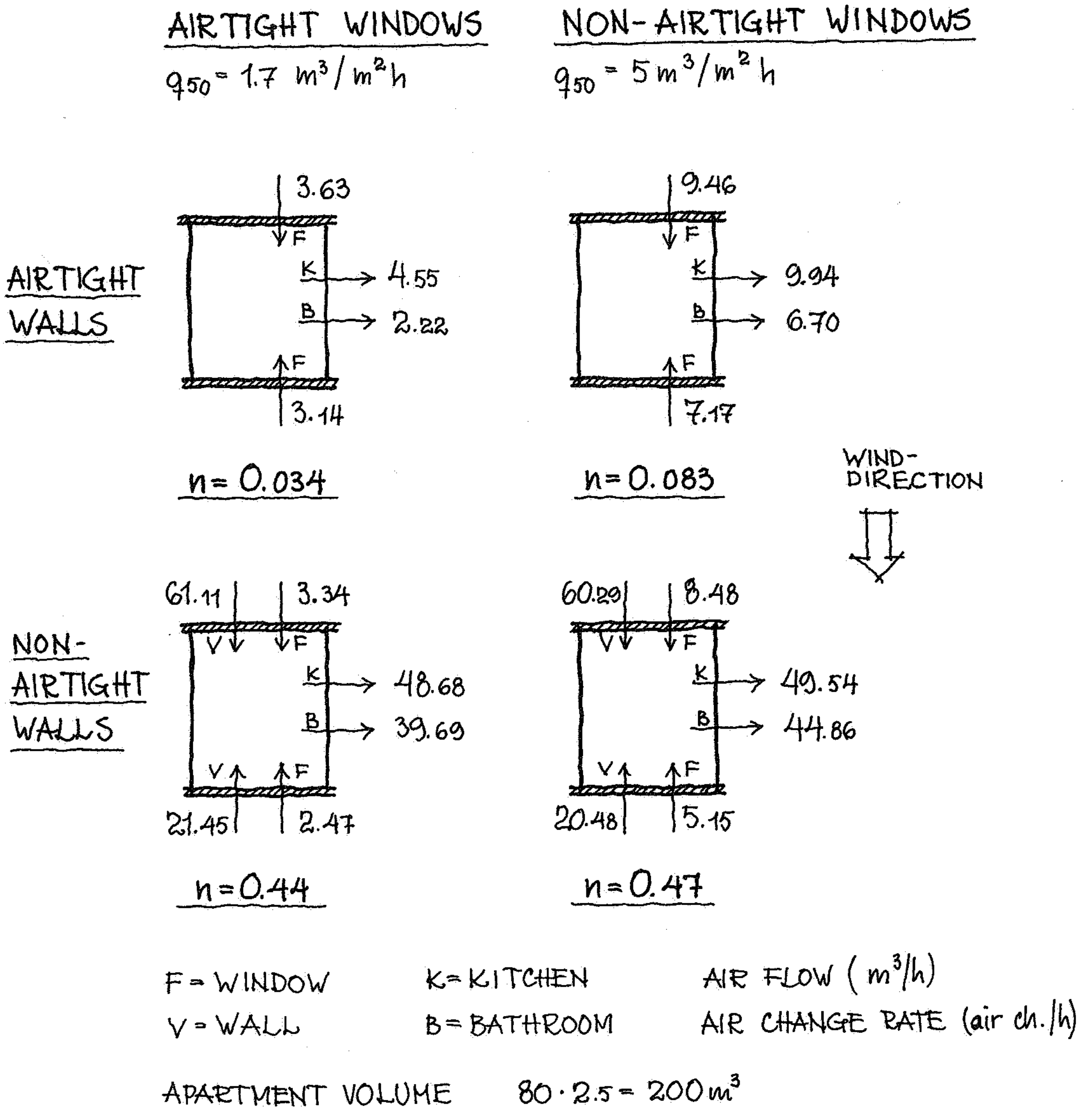


Figure 5 Results of the JK-CIRCUS computer calculation for a naturally-ventilated flat in a block of flats. Wind velocity = 4 m/s.

The mean value of as-measured normal ventilation in the naturally-ventilated flats is 0.47 air changes/h, i.e. approximately the same value as shown in the figure above for poorly airtight walls and windows. It therefore seems reasonable to assume that older flats have approximately the airtightness of walls and windows as used in the calculation case, and for which the air change rate at a differential pressure of 50 Pa (n_{50}) is 1.5 air changes/h. Putting it another way, this means that the airtightness of walls and windows in older flats is such that the n_{50}-value is about 1.5 air changes/h, which should be compared with the standard n_{50}-value for a block of flats of 1.0 air changes/h.

It can be seen from the figure that the air change rate in the flat is very little affected by the airtightness of the windows. This means that, if a badly-fitting window as above is weather-stripped so that its airtightness at a differential pressure of 50 Pa meets the Building Regulations requirements, then the air change rate in the flat would be reduced by only 0.05 air changes/h or 0.03 air changes/h respectively, depending on the airtightness of the walls. For windows with even poorer airtightness, $q_{50} = 10$ m³/m²h, the air change rate would be 0.16 air changes/h if the walls were airtight and 0.52 air changes/h if they were not. Weatherstripping the windows to meet the requirements of the Building Regulations in this case would result in reductions of air change rates of 0.13 air changes/h and 0.08 air changes/h respectively, i.e. somewhat more than before, but nevertheless not very much.

The air change rate is therefore largely dependent on the airtightness of the walls. That this is so is due to the fact that the wall area is large in proportion to the window area, with the result that a wall with poor airtightness will have more effect than a window with poor airtightness.

For the flat in the worked example, the air change rate at a differential pressure of 50 Pa, n_{50}, can be expressed as a function of the airtightness of the walls and of the windows as:

$$n_{50} = 0.144\ Tv + 0.056\ Tf$$

where Tv = airtightness of the wall (m^3/m^2h)
Tf = airtightness of the window (m^3/m^2h)

It can be seen from the expression that any change in wall airtightness will have a greater effect on the air change rate than an equal change in window airtightness.

3. THE EFFECT OF OUTDOOR CLIMATE ON AIR CHANGE RATE - COMPUTER CALCULATIONS

3.1 Prerequisites

The ventilation in naturally-ventilated buildings depends on current wind and temperature conditions. Wind pressure and chimney effect vary with wind velocity and indoor/outdoor temperature difference respectively.

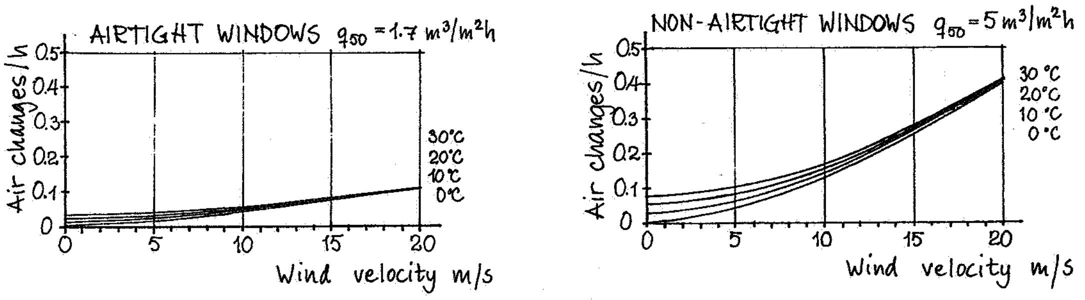
In order to investigate how wind and temperature influence ventilation, the air change rate in the flat illustrated in Figure 3 has been calculated using the JK-CIRCUS program for different wind velocities and different indoor/outdoor temperature differences. Other data are the same as before.

3.2 Results

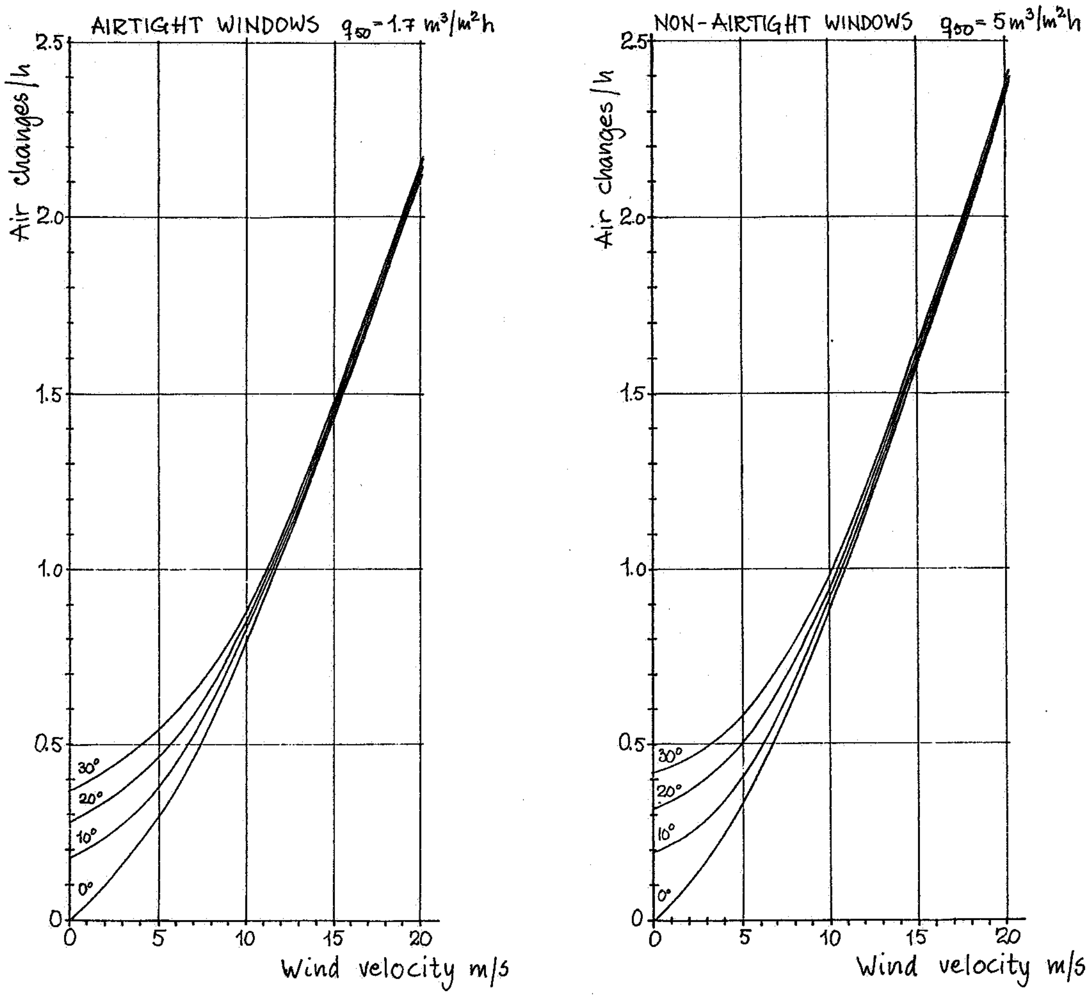
The results of the calculations are illustrated in Figure 6. It can be seen that, at low wind velocities, it is the temperature difference (chimney effect) that has the greatest effect on air change rate. The greater the temperature difference, the higher the ventilation air change rate. At high wind velocities, on the other hand, the wind pressure becomes dominant, with the air change rate being almost independent of temperature difference.

Poorly fitting windows increase the air change rate by up to 0.1 air changes/h when the wind velocity is low, i.e. less than 10 m/s. At higher wind velocities, poorly fitting windows result in increases in air change rate of 0.15-0.3 air changes/h, depending on the airtightness of the walls.

If we consider the routes taken by the airflows through the flat, we can see that, at low wind velocities, air leaks in through both the windward and lee sides, varying slightly depending on the airtightness of the walls. This inward leakage increases with greater temperature difference. As the wind velocity increases, so inward leakage of air through the windward wall increases, but decreases through the lee wall. At high wind velocities, above 10 m/s, inward leakage occurs only through the windward wall, with air leaking out instead through the lee wall, due to the fact that the effect of wind pressure is greater than the thermal chimney effect. This results in draughts through the apartment, although air is being evacuated through the ventilation ducts all the time.



A. AIRTIGHT WALLS



B. NON-AIRTIGHT WALLS

Figure 6 The effect on air change rate of wind velocity and indoor/outdoor temperature difference for airtight and non-airtight walls and windows. Natural-draught ventilation in the flat as shown in Figure 3.

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