AIC TRANSLATION NO. 13

Proposal for method of calculating air infiltration in a multi-storey building.

Translated from the original Italian:
"Proposta di metodo per il calcolo delle infiltrazioni d'aria in un edificio multipiano"
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La Termotecnica, Vol.XXXV, No.2, Feb.1981, p62-6€

Proposal for a method of calculating air infiltration in a multistorey building(*)

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Abstract - In this paper a method is described, discovered after much bibliographical research, for air infiltration calculation in a multistorey building. The method which has been developed may be used both for computer calculations, in order to determine the thermal "balance sheet" for a building hour by hourand for steady state manual calculations. Analytical and experimental reports have been examined to determine the air flow-rate due to the wind and the temperature-induced convection (stack effect). The air flow-rate has been evaluated as a function of the pressure difference, taking into account the dynamic pressure distribution around the building, and, as for the window air tightness, the classification according to Standard UNI EN42. An example of the calculations has been included.

1. Effect of the wind

1.1. Reducing meteorological wind to local wind

By meteorological wind is meant the values of wind direction and velocity, measured at a meteorological station at a height above the ground of z_s (generally z_s = 10 m).

By local wind is meant the values of wind direction and velocity in the place where the building is erected at a height above the ground of z.

In the calculation method described, the wind direction is not varied. It is indeed true that this may be varied by the presence of natural or artificial obstacles (high buildings in an urban area, for example), but the deliberate variation of this value would require a detailed knowledge of the topography of the area in which the building is erected, thereby encumbering the calculation method with an excess of information.

The formula used to reduce this wind velocity from the meteorological station to the site on which the building is erected (and at height z from the ground) is as follows (5, 30):

$$v_z = v_s \, (d_s/z_s)^{\beta_s} \, (z/d_e)^{\beta_e} \qquad (1)$$

the factor s relating to the meteorological station and the factor e to the building.

The values of β and d are given in tab. 1 as a function of some typical land formations.

1.2. Calculation of the pressure difference through a wall in any direction in relation to the wind direction

When the wind encounters an obstacle, its velocity is altered around this obstacle. If the kinetic energy of the air is reduced, there will be an increase in the compressive energy and vice versa.

(*) Work carried out as part of the Completed Energy Project of the CNR. Sub-Project RERE, Subject D, Contract 78.01196.92.

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In several cases. the word "window" has been used to translate the Italian "serramento", which would seem to be a term embracing also doors and wall apertures.

	d (m)	1/β
country (rural)	280	7
periphery (outskirts) of town or busy country town	400	3.5
urban centre	520	2.5

Table 1.

If all the kinetic energy is converted to compressive energy, the increase in the latter in relation to the existing pressure in the flow of air not disturbed by the obstacle would be (14) :

$$\Delta p_w = 1/2\, \rho v_z^2 = 0.647\ v_z^2 \qquad (2)$$

The value of the density of air introduced in (2) corresponds to 0°C. For temperatures of between -10°C and +10°C, the value of the air density may be obtained from the following linear relation:

$$\rho = - 0.00475\ t_e + 1.294 \qquad (3)$$

Generally speaking, on a wall facing in any direction in relation to the wind direction, there will be an increase (or reduction) in the static pressure, equal to (5, 14):

$$p_w = p = \Delta p_w = C_p \ .\ 0.647\ v_z^2 \qquad (4)$$

With C_p between - 1.0 and + 1.0.

The pressure coefficient C_p assumes positive values close to unity in respect of the windward wall of the building, whilst it generally assumes negative values on the lateral and leeward walls.

A positive value of C_p represents a state of excess pressure on the wall, with a consequent immission of air from the outside. The opposite is true if C_p is negative, when the wall is subject to low pressure and the air flows from the inside to the outside.

The determination of the pressure coefficient is one of the most complex and controversial subjects. It depends both on the wind direction and on the geometric characteristics of the building (17).

The values of C_p on each wall are given in table 2 as a function of the angle of incidence α between the wall and the wind and of the ratios l:w and h:w between the dimensions of the building (20).

Conventionally, the walls of the building are defined on the following criterion (fig. 1): A is the windward wall on which the wind acts from the right, C is the windward wall on which the wind acts from the left, B is located in front of A, D in front of C.

Consequently the angle α varies from 0° to 90°.

The value of Δp_w obtained from (4), as already mentioned, represents the variation of the pressure on the wall in relation to the flow undisturbed by obstacles.

$h/w < 1/2$	$1 < l/w < 3/2$	$C_p =$ A) $-1,2\alpha/90 + 0,7$ B) $-0,3\alpha/90 - 0,2$ C) $1,2\alpha/90 - 0,5$ D) $0,3\alpha/90 - 0,5$
	$3/2 < l/w < 4$	$C_p =$ A) $-1,2\ \alpha/90 + 0,7$ B) $-0,25\alpha/90 - 0,25$ C) $1,3\ \alpha/90 - 0,6$ D) $0,5\ \alpha/90 - 0,6$
$1/2 < h/w < 3/2$	$1 < l/w < 3/2$	$C_p =$ A) $-1,3\ \alpha/90 + 0,7$ B) $-0,35\alpha\ 90 - 0,25$ C) $1,3\ \alpha/90 - 0,6$ D) $0,35\alpha/90 - 0,6$
	$3/2 < l/w < 4$	$C_p =$ A) $-1,2\alpha\ 90 + 0,7$ B) $-0\ 2\alpha/90 - 0,3$ C) $1.4\alpha/90 - 0,7$ D) $0,6\alpha/90 - 0,7$
$3/2 < h/w < 6$	$1 < l/w < 3/2$	$C_p =$ A) $-1,6\ \alpha/90 + 0\ 8$ B) $-0,55\alpha/90 - 0,25$ C $1\ 6\ \alpha/90 - 0,8$ D) $0,55\alpha/90 - 0,8$
	$3/2 < l/w < 4$	$C_p =$ A) $-1,2\alpha/90 + 0,7$ B) $-0,1\alpha/90 - 0,4$ C) $1,5\alpha/90 - 0,7$ D $0,6\alpha/90 - 0,7$

Tab. 2

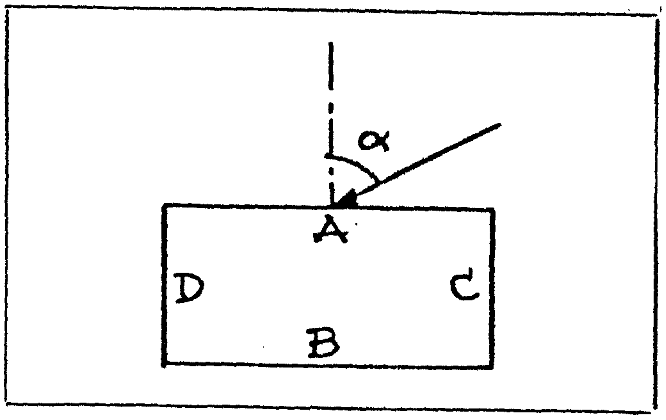

Fig. 1

On the other hand, the physical value determining the passage of air through the wall components is the pressure difference between inside and outside, a function of the pressure which is established inside the building, p_i. Now because the internal pressure is generally different from the atmospheric pressure, it would be necessary to introduce in (4) a coefficient C'_p in place of C_p, so that:

$$p_w - p_i = \Delta p'_w = C'_p \cdot 0.647\ v_z^2 \qquad (5)$$

However, in order to know C'_p, the internal pressure would have to be calculated at every moment: this depends on the resistance and arrangement of the openings and on the cracks through which the air passes. If these are distributed uniformly around the walls, the internal excess pressures (or low pressures) will not exceed 20% of the maximum value obtained from (2). Otherwise, with most of the openings located on the windward wall, for example, internal excess pressures may be obtained which are almost equal to the excess pressure on the windward surface (14).

However, because the variations in internal pressure do not - on the same storey- lead to any variation in the sum of the absolute values of the pressure differences between the inside and outside, the problem may be simplified substantially by considering the pressure coefficients C to be equal to the pressure difference coefficients C'_p. This is tantamount to considering the pressure inside the building to be equal to the atmospheric pressure.

2. The stack effect

When the inside temperature is higher than the outside temperature, the stack effect, due to the difference in air density, produces an internal low pressure on the low storeys and an internal excess pressure on the higher storeys.

Consequently there is a horizontal plane, called the neutral plane, in which, in the absence of other phenomena, the internal and external pressures are equal.

Generally speaking the difference between internal and external pressures due to the stack effect is given by (14, 5):

$$\Delta p_c = 0.0342\ p\ y\ (1/(273 + t_e) - 1/(273 + t_i)) \qquad (6)$$

According to the choice of symbols for (4), the distance from the neutral plane must be measured positively downwards and negatively upwards.

The determination of y requires a knowledge of the height of the neutral plane from the ground (z_{pn}), which in turn depends upon the distribution of the vertical flows and the internal partitions.

Generally speaking, the stack effect is accentuated by the presence of internal vertical air cavities, and if these are vertically distributed in a uniform manner, the neutral plane will be located half way up the building.

If the opposite is true, i.e. if the area separating one storey from another is completely airtight, there will be as many neutral planes as there are storeys in the building, located halfway between the floor and ceiling.

In 1-2 storey buildings (residential houses, etc.), the neutral plane is generally higher than the centre line, being situated halfway up the chimney (if there is one):

$$z_{pn} = 0.6\ h \div 0.7\ h$$

For higher buildings, it is found (27, 28) that z_{pn} varies between 0.3 h and 0.7 h. These values have been obtained experimentally, and for a few cases only, and because these results have not yet enabled simple, general relationships to be deduced between the morphological characteristics of the building and the position of the neutral plane, it is suggested that the following is assumed:

$$z_{pn} = 0.5\ h \qquad (7)$$

3. Calculation of the rate of infiltrations due to the combined action of the wind and stack effect

The general equation defining the rate of infiltrations through a wall component is as follows (13, 14):

$$Q' = C\ (\Delta p)^n \qquad (8)$$

The coefficient of flow C is defined as the volumetric flow rate per unit of length of the crack or per unit area of the component, corresponding to a pressure difference of 1 Pa.

Q' represents the volumetric flow rate per unit of length of the crack or per unit area of the wall component and is measured in (m3/h . m) and (m3/h.m2) respectively.

In (8) Δp is the algebraic sum of the pressure differences due to the effect of the wind and the stack effect:

$$\Delta p = \Delta p_w + \Delta p_c \qquad (9)$$

It is noted that the rate of infiltrations due to the combined action of the wind and the stack effect is not the sum of the rates due to the individual effects, because the ratio between Q' and Δp is not of the linear type.

The value of the exponent of flow n, generally used both for cracks and thin openings and for walls, is 0.65 (13, 14, 26, 28).

The value of C is closely associated with the quality of the wall and the windows, particularly in the matter of their impermeability to air (29).

Based on this impermeability, the windows can be graded into 3 UNI classes designated A1, A2, A3, to which the maximum values of C listed in table 3 correspond (18, 19):

Table 3

	A1	A2	A3
$C (m3/hPa^n.m)$	0.60	0.30	0.10

To obtain the rate of infiltrations through all the windows, it would then be necessary to multiply the result in (8) by the length of the aperture.

$$Q = Q' \cdot L \qquad (10)$$

Similarly, the losses through a wall component permeable to air may be calculated (an outer wall, for example), by introducing the coefficients of flow and the area of the wall component into relation (8) and into the following one:

$$Q = Q' \cdot A \qquad (11)$$

We give below in table 4 the values of the flow coefficients C deduced from the (available) literature, for some walls:

Type of wall or structural element	Thickness (m)	C ($m3/h.Pa^n m^2$)
outer wall of rendered (plastered) brickwork (31)	0.40	0.063
ordinary brickwork (31)	0.065	0.001
double timber wall (31) lined with building paper and wood	0.124	0.077
wall of bricks and rendering (16)		0.22

Table 4.

Complete calculation example

Assume, for example, that there is a 4-storey building, of rectangular plan ($h = 14$ m, $l = 20$ m, $w = 10$ m), situated in Turin, on the outskirts ($d = 400$ m, $\beta = 1/3.5$), with the long wall in the SW-NE direction (i.e. set at an angle of 315° in relation to North). The inside temperature is maintained at $20^\circ C$.

Moreover, the hourly temperature values, wind direction and velocity and, possibly, pressure are known, among other things (otherwise $p = 10^5$ pa is assumed), as measured at the Aeronautical Meteorological Station of Caselle (rural values: $d_s = 280$ m, $\beta_s = 1/7$).

The effects of the air permeability of the outer walls are disregarded. At a particular time, the following values prevail:

time	t_e	d	v_s	p
.	.	.	.	.
τ	$0^\circ C$	30°	3.5 m/s	10^5 pa
.	.	.	.	.
.	.	.	.	.

The intention is to calculate the rate of infiltrations by the combined action of the wind and the stack effect through a window of the type UNI A1 to 2 leaves (1.20 x 2.00 m), installed in a room (4 x 4 x 3 m) on the fourth storey, facing the long wall to the south east i.e. at an angle of 135° in relation to north always in the clockwise direction.

The average height of the storey is therefore $z = 14/4 \times 3 + 1.5 = 12$ m.

1) Calculation of v_z :

From (1): $v_z = 3.5\ (280/10)^{1/7}\ (12/400)^{1/3.5} = 0.591 \times 3.5 = 2.1$ m/s.

2) Calculation of Δp_w:

From (4): $\Delta p_w = C_p \cdot 0.647 v_z^2$.

From table 2, since $1/2 < h/w < 3/2$, $3/2 < l/w \leq 4$ and since α (see fig. 2) is equal to 75°, the value of C_p through wall B is obtained:

$$C_p = -0.2\alpha/90 - 0.3 = -0.2 \cdot 75/90 - 0.3 = -0.47.$$

By introducing this value into (4), the following is obtained:

$$\Delta p_w = -0.47 \cdot 0.647 \cdot 2.1^2 = -1.3 \text{ pa}$$

3) Calculation of Δp_c:

From (6) :

$$\Delta p_c = 0.0342 \text{ py } (1/(273 + t_e) - 1/(273+t_i)) = -4.3 \text{ pa}$$

where:

$p = 10^5$ pa $\qquad$ $y = 7 - 12 = -5$ m

$t_e = 0^\circ C$ $\qquad$ $t_i = 20^\circ C$.

4) Calculation of the rate of infiltrations:

$$\Delta p = \Delta p_w + \Delta p_c = -5.6 \text{ pa} \quad \text{from (9)}$$

$$Q' = C|\Delta p|^n$$

Since C, for UNI-A1 windows, is equal to 0.6 and n = 0.65, the following is found:

$$Q' = 0.6\ (5.6)^{0.65} = 1.84 \text{ m3/h . m}$$

For the window examined:

L = 2.00 x 2 + 1.20 x 2 + 2.00 = 8.40 m

And finally, for (10) :

Q = Q'.L = 1.84 . 8.4 = 15.44 m3/h.

Since the intention is to evaluate the losses due to infiltrations in (atmospheric volumes)/hour, the following is obtained:

V = 4 x 4 x 3 x 48 m3

Q = 15.44/48 = 0.32 V/h.

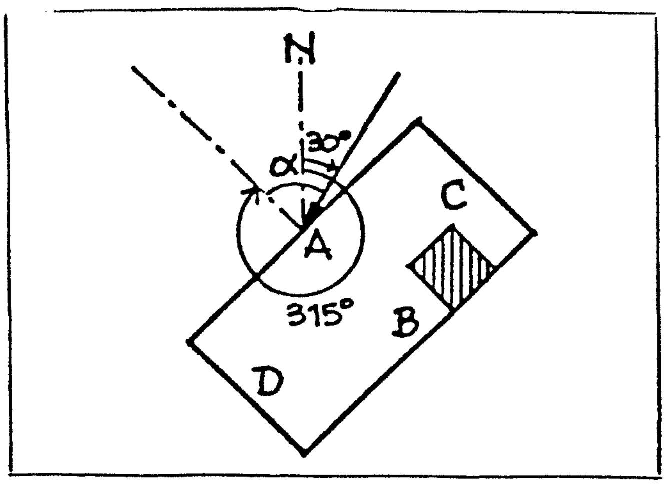

Fig. 2.

Symbols

d thickness of the boundary layer, (m);

z height from the ground of the area considered (m);

z_s height from the ground of the anemometer, (m);

β characteristic index of the boundary layer;

v_z local wind velocity at height z, (m/s);

v_s meteorological wind velocity, (m/s);

h height ofthe building, (m);

w width of the building, (m);

l length of the building, (m);

y distance from the storey under consideration to the neutral plane, (m);

z_{pn} height from the ground of the neutral plane, (m);

ρ weight per unit of volume, (kg/m3);

C_p pressure coefficient;

C'_p pressure difference coefficient;

p atmospheric pressrue, (pa);

p_i internal pressure, (pa);

p_w pressure of the wind on the wall, (pa);

Δp_c pressure difference between inside and outside due to the stack effect, (pa);

Δp difference between internal and external pressure due to the combined effect of the wind and stack effect, (pa);

t_e outside temperature, (^oC);

t_i inside temperature, (^oC);

n flow exponent

C flow coefficient (defined in the text), ($m3/h.pa^n m$) or ($m3/h . pa^n m^2$);

Q' unit air flow-rate, (m3/h.m) or (m3/h.m2);

Q air flow-rate, (m3/h);

L length of the equivalent crack (opening), (m)

A area of the wall component, (m2);

α angle of incidence of the wind on the wall, (degrees);

Φ ,angle of origin of the wind (in the clockwise direction from the North), (de- degrees);

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