PROCEDURES FOR CALCULATING VENTILATION IN ROOMS WITH OPEN WINDOWS

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ABSTRACT

Calculation procedures are presented for air flows in buildings which are caused by the combination of: turbulent air flows at the outside of open windows, temperature differences, the average effect of moving objects and thermal turbulence, and static pressure differences. The last are caused by the mean static wind-pressure differences on the envelope of the building and also by mechanical ventilation systems.
Simple formulas, known in the literature, are used to calculate the air flows caused by the individual forces. The total flows can be determined using the formulas and rules of thumb which have been derived from the calculation results. Several types of windows with detailed information on sizes and opening angles are taken into account. The uncertainty of the results, when wind forces are involved, is still large, due to the badly known relation between the wind speed on roof level and near by the windows. Nevertheless, knowledge about the mean, the minimum and maximum values of the total air-flows are useful.
An easy to use PC-program has been developed to execute the procedures.

1. INTRODUCTION

The project on ventilation was financed by the Dutch Government Building Agency, Dept. Advice and Research, The Hague. There is a need for procedures to determine the ventilation in rooms with open windows. Up till now calculated summer temperatures in buildings are based on rough estimations on ventilation. The Building Agency intends to introduce standards determining the ventilation used in simulation programs.
Defining ventilation is hard when it concerns a room with several flows to and from the outside and other inner spaces, and possibly provided with a mechanical ventilation system. Rooms with open doors or other openings in inner walls may get more fresh air from inner spaces than through the open window in the room itself. Essential is the air quality in the room, which is related to the temperature and the amounts of H_2O, CO_2 and other pollutions. To determine this air quality one must be able to calculate all the flows. With these considerations in mind the word ventilation will be used in this paper for all types of air flows. Even if the flows and their air properties are known, the air quality in the room may locally vary a lot, due to imperfect mixing. However that subject lies besides the scope of this paper.
In the paragraphs 2 up to 5 a summary is given of the theory and the formulas about air flows through openings caused by several individual driving forces.
Paragr. 6 describes the calculation principals of correction factors for the flows through vertical and horizontal hinged windows.
Paragraph 7 is dedicated to the effects of combinations of driving forces. Rules of thumb are presented to determine the total in- and outflow through an opening. At last we discuss the PC-program and desired further research.
Besides this short paper one can find more details in the full report (1).

2. AIR FLOW THROUGH AN OPENING

$$Q = c \cdot A \cdot \Delta p^b \quad [m^3/s] \qquad (1)$$

The flow through an opening of A m^2 can be approximated with formula 1. Δp is the difference of static pressures at both sides of the opening, as can be measured at spots where the velocity is negligible. The power b has a theoretical value of 1 for laminar flow. The value decreases to 0.5 for very turbulent flows as such through windows. The factor c is depends on b. Lit. (2) gives an overview of proposed values of b and c as mentioned in several publications for calculating flows through cracks in building structures. In (3) is stated that commonly used values for openings like windows are: c=0.827 and b=0.5; for flows through cracks in recent dwellings the values determined by measurement are: c=0.59 and b=0.65; for the combination of cracks and open windows satisfactory values are: c=0.82 and b=0.53. In more detail formula 2 can be used (lit. 2,4/7):

$$Q = Cd \cdot A \cdot (2/\rho)^b \cdot \Delta p^b \quad [m^3/s] \qquad (2)$$

For turbulent flows at windows, doors and ventilation openings, measurements confirm the theory that Cd=0.61 is suitable if $T \leq 20°C$ (6). ρ is the specific mass of air [kg/m^3]. Using =1.21 (T=18°C, 50% rel. moisture) and b=0.5 formula 2 is identical to formula 1 with c=0,78 .
The formulas can also be used to calculate the flow at a cascade of several openings with areas: A1, A2, ... m^2. The effective area A of the cascade can be calculated as follows for two or more openings:

$$A = A1 \cdot A2/(A1^{1/b} + A2^{1/b})^b \qquad \text{or:} \qquad 1/A^{1/b} = 1/A1^{1/b} + 1/A2^{1/b} + \ldots \qquad (3)$$

3. Ventilation caused by temperature differences

When the air in a room has a temperature difference ΔT to the outside, then buoyancy causes a pressure difference Δp which is proportional to the vertical level difference h :

$$\Delta p = g \cdot h \cdot \rho \cdot \Delta T/T \quad [Pa] \qquad (4)$$

g is the gravity acceleration (9.81 m/s^2 at see level).
ΔT is the average of the in- and outside temperatures.
Together with formulas 1 (or 2) and 3 one can calculate the flow which will occur in two horizontal openings in cascade (see figure 1a). If one or both openings are not horizontal, then the situation is more complicated because the pressure varies in vertical direction. In §7 a solution is given. In case of only one not horizontal opening the temperature difference will cause equal flows in and out through the opening. The warmer air passes through the upper part of the opening and the colder air passes the lower part in opposite direction. The total flow in both directions can be approximated by integration across the opening of the local flow, calculated with formulas 1

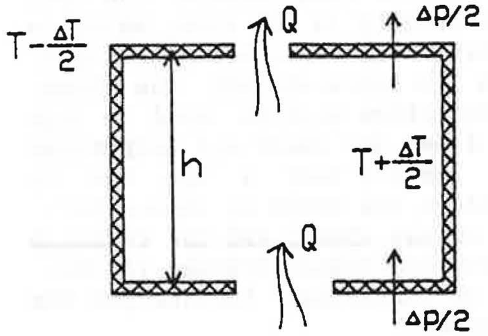

FIGURE 1a. Thermally driven airflows through two openings in cascade.

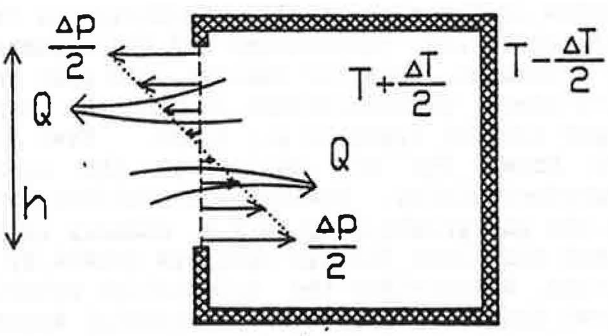

FIGURE 1b. Thermally driven airflows through a window.

(or 2) and 4. For vertical openings like windows and doors the result is:

$$Q = Cd/3 \cdot A \cdot (g \cdot h \cdot \Delta T/T)^{1/2} \quad [m^3/s] \qquad 5$$

A is the total area of opening; h is the height in the opening (see fig.1b).

4. Ventilation caused by static wind pressure

Every wind direction creates a different pattern of pressure levels around a building. This paragraph is dealing with pressure levels which are an average over a period long enough to flatten out turbulence. The pattern is very dependent on the shape of the building. Pressure patterns of some simple shapes are specified in the literature (2,7,8,9). The local pressures at walls and roof are given by coefficients C representing fractions of the static wind pressure:

$$p = C \cdot ½ \cdot \rho \cdot V^2 \quad [Pa] \qquad 6$$

V is an average wind speed which can be derived from the local meteorological wind speed with corrections for the roughness of the surrounding area, and for the height of the building. When the building is lower than the mean height of obstacles in the environment, then this mean height is relevant to determine V. Procedures and tables for corrections can be found in lit. (2,7,1)
The flows in a building, as a result of the pressure differences on the envelope, can be calculated by solving a set of equations in which the openings in the envelope and between rooms are taken into account. Each equation (formula 1 or 2) relates the pressure difference across an opening to the corresponding flow.

5. Ventilation caused by turbulence

Air turbulence causes fluctuations of the local pressure on the outside of the building. Dependent on the inducement of the eddies, the wavelengths are very various. One may divide the wavelengths in three classes (7,10):
1. Long wavelengths (in relation to the building size) induced by wind around obstacles in the environment and by thermal disturbances. The contribution to the total ventilation is relatively small (4).
2. Wavelengths comparable to the building height are induced by wind and the main shape of the building itself. Around the building the correlation of the fluctuating pressure components varies from zero to one. A theoretical approach (7) shows that the ventilation increases proportional to the turbulence rate. At a rate of 30% the ventilation through windows increases with 20 and 25% for zero resp. full correlation; the flows through cracks increase with 45 and 60% (compared to a situation of static wind pressure).
3. Short wavelengths are induced by winds in direct contact to the building surface. However the turbulent layer can separate from the surface. Therefore the shape and the wind direction are of great influence on the local intensity of these eddies. Eddies with wavelengths comparable to the size of windows may be responsible of the main part of the ventilation in rooms when open windows (in one wall) are the only openings (10). Due to the complexity of the air flow around the building it is not (yet) possible to give an accurate procedure to determine the frequency spectrum of the local flow. For the time being one can use formula 7 to determine the mean in- and outflow through one or more windows in one facade of a for the rest closed room (4).

$$Q = c \cdot A \cdot V \ [m^3/s] \qquad \text{with:} \quad c = 0.02 \text{ to } 0.08 \qquad 7$$

V is the corrected mean windspeed on roof level (§4). A is the area of opening of the window(s). Coefficient c determines the minimum and maximum values which can be expected on different locations of a normal shaped building (4).

6. CORRECTION FACTORS FOR HINGED WINDOWS

Of course the flow through windows is influenced by the angle of opening and the type of construction. First of all the window-angle determines the area of opening. Also the shape of the opening varies with the window-angle. This is important when there is a temperature difference. The interaction between an air flow along the facade and a window which is turned to the outside, may influence the flow through the window. However measurements show that the influence of the direction of the flow along the facade may be small due to turbulence of the outside flow (4). In our calculations we did not take into account a relation to wind-direction.

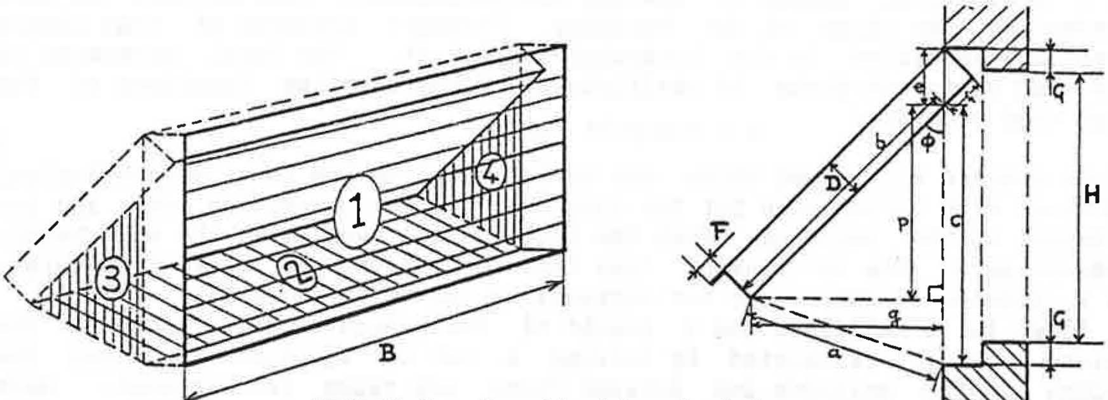

FIGURE 2. Topside hinged window.

Figure 2 shows a window with hinges on the topside. With this type of window the effective vertical height in the opening (essential in case of a temperature difference) is zero or very small at small angles of opening.
We have developed correction factors which can be applied to the results of formulas 1,2,5 and 7 in which the full area $A=H \cdot B$ is filled in. The factors are the results of a series of linear and nonlinear equations and therefore cannot easily be approximated by simple formulas. For nonthermally driven forces an effective area of opening has been calculated as a cascade of the openings 1 and 2+3+4. For thermally driven forces the positive vertical heights in the openings 2,3 and 4 are taken into account. Figure 3 shows an example of the correction factors for some specific sizes. The curves $A_{eff}/B \cdot H$ give the corrections for nonthermally driving forces; the curves J give the corrections for thermally driven forces.

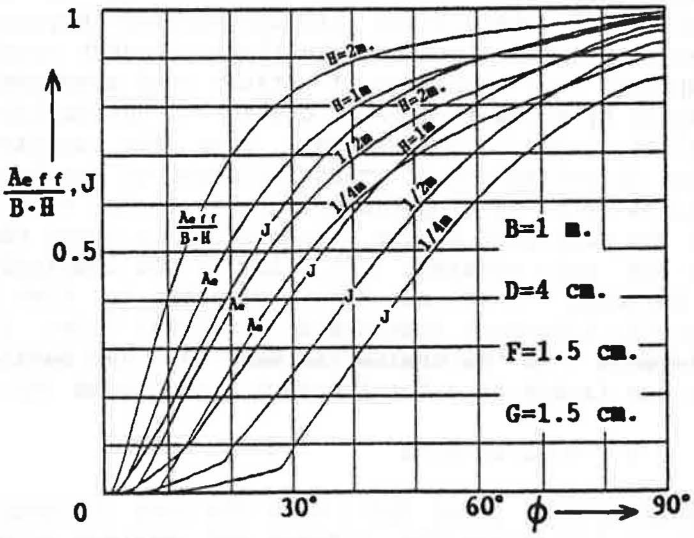

FIGURE 3. Ventilation for various height/width ratios.

In a similar way the correction factors are calculated for vertical hinged windows. With those the curves J are on a much higher level for small angles. To use the correction factors there are three options: 1. Use the computer-program which we have developed; 2. Use the graphs in (1) for some usual sizes of windows; 3. Implement the calculation procedures (1) in your own programs.

7. AIR FLOW AS A RESULT OF SEVERAL DRIVING FORCES

At a large opening the local pressure may vary across the opening. We assume that it is acceptable to add the local pressures caused by different driving forces and to determine the total flows by integration the local flows (formula 2) across the area of the opening. These calculations are performed for a vertical square opening and for combinations of three types of pressure patterns: 1. Uniform pressure, caused by static wind pressure around the building, or by a mechanical ventilation system; 2. Thermal pressure (figure 1b), caused by a constant temperature difference between both sides;
3. Horizontal sine shaped pressure with wavelength equal to the width of the opening, representing a turbulent pressure in front of windows caused by wind and inside rooms due to moving objects. (Abbreviations: **Uni**, **ΔT** and **Tur**)
In two tables the total in- resp. outflow is printed for a constant uniform pressure and wide variations of the temperature difference and the mean windspeed at rooflevel. These tables may be used for vertical openings in all sizes. The procedures are given to perform the correct scaling (1).
Figure 4 is the representation of the first row and column of both tables.
Q^+ is the flow in the direction of the uniform pressure vector; Q^- is the flow in opposite direction. Striking is the initial descent of the flow, when ΔT or the windspeed (V) is risen in combination with a constant uniform pressure. This is a result of the quadratic relation between pressure and flow. The results for ΔT and Tur are almost the same.
If also a stochastic distribution of the sine-amplitude would be incorporated, then it may be expected that Q^- will drop to zero more gradually. Such improvements may be valuable when verification measurements have proved our theorems. Figure 5 shows the results for combinations of a constant ΔT and a variable windspeed. Here is no dip. V is determined using the average c=0.04 in formula 7. The flow can be approximated very well with the formula:

$$Q = (Q_{\Delta T}^6 + Q_{Tur}^6)^{1/6} \quad 8$$

Q_{Uni} is the flow caused by only a uniform pressure difference.
$Q_{\Delta T}$ is the flow in both directions caused only by a temperature difference.
Q_{Tur} is the flow in both directions caused only by turbulent air flows.
These flows can be calculated with the formulas 1,2,5 and 7.

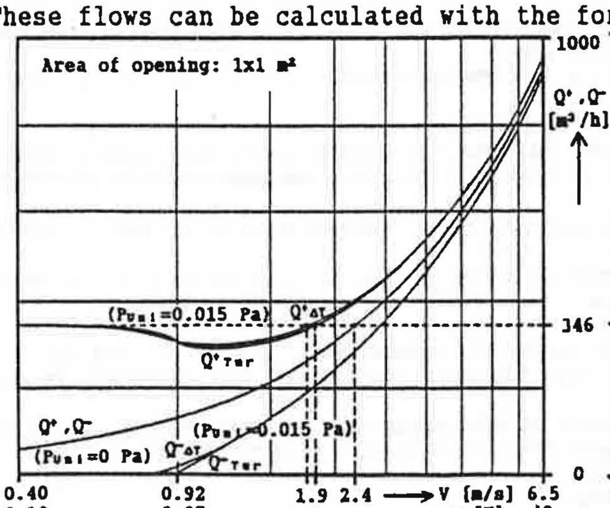

FIGURE 4. Airflows through a vertical opening with a constant uniform pressure difference.

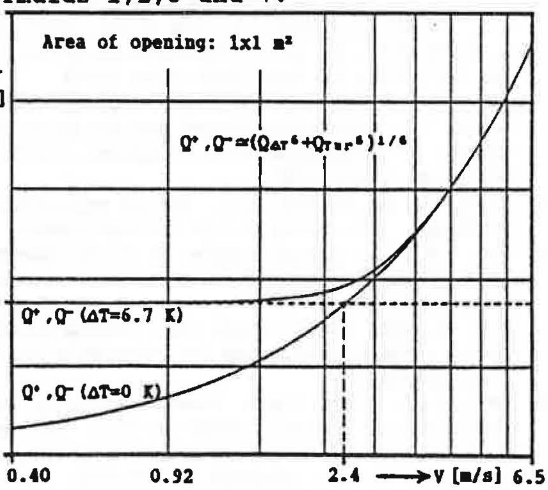

FIGURE 5. Airflows through a vertical opening with a constant temperature difference.

The results differ remarkable from the frequently used formula:
$Q = (Q_{\Delta T}^2 + Q_{Tur}^2)^{1/2}$ which is used in the literature (2,6,11) for calculation of total flows. This formula is correct only when pressures of the same type are combined (only uniform, thermal or turbulent).
In many situations a larger error-margin is acceptable than might be obtained with use of the tables. This is especially true when wind is mainly responsible for the ventilation. One can use the following **rules of thumb** of which the results are within 20% deviation from those of the tables:

Rule 1:
For the combined pressures: p_{Uni} + ($p_{\Delta T}$ and/or p_{Tur}) the flow in opposite direction of the vector p_{Uni} can be determined as follows:

If ($Q_{\Delta T}$ or Q_{Tur}) > Q_{Uni} then $Q^- = \max.(Q_{\Delta T}$ and $Q_{Tur}) = Q_{max}$.
If ($Q_{\Delta T}$ and Q_{Tur}) < Q_{Uni} then $Q^- = Q_{max} - (Q_{Uni} - Q_{max})/2$ if $Q^- > 0$
else $Q^- = 0$.

Rule 2:
The flow in the same direction as the vector p_{Uni}, and the flows in both directions for combinations of $p_{\Delta T}$ and p_{Tur}, are equal to the largest of the separate flows: Q_{Uni}, $Q_{\Delta T}$ and Q_{Tur}.

8. CONCLUSION

To use the calculation procedures in full extend the help of computers can be very useful. An easy to use PC-program has been developed to determine the flows, the fresh air ventilation rates and the CO_2 percentages in a cascade of two rooms separated by a corridor. The user can vary all parameters discussed in this paper. The results are the mean, the minimum and the maximum values to be expected. The program runs as a macro in Lotus 1,2,3 and Symphony. We consider to develop a stand alone program with graphic support and with more complicated building models and more window types.
Though aware of the fact that the time was to short to study all the relevant literature and to perform verification measurements, we hope this study contributes to the realization of useful calculation methods. Last year's students are invited to do further theoretical and experimental research on the verification of the calculation procedures with combined driving forces, the imperfect mixing at turbulence driven flows through windows, and the frequency spectrum of airflows in front of windows on several locations of a building in relation to the wind variables and the environment.

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