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Ventilation Through a Single Opening in a Scale Model

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1. Introduction

Little is known about the ventilation through one single window in an enclosed space. It is important to gain more knowledge in this field. This kind of ventilation can be investigated by measurements in buildings or in scale models in a wind tunnel. We chose for measurements in a scale model, because in this way the influence of various factors such as velocity, window dimensions etc. on the ventilation can be examined systematically. However, a disadvantage is that the results refer to a room and window opening which are much smaller than in reality. It is necessary, therefore, to examine the influence of possible scale effects on the measuring results by measurements in existing buildings and homes. By simulating as well as possible the atmospheric turbulence in the wind tunnel we tried to reduce the scale effect to a minimum.

In this investigation, only the isothermal ventilation caused by the wind is examined. Thermal effects on the ventilation are not considered.

2. The Scale Model in the Wind Tunnel

For the measurements a cubical model of 0.3 x 0.3 x 0.3 m^3 was used. If required the model could be enlarged in one horizontal direction using perspex auxiliary pieces measuring 0.3 x 0.3 m^2 in cross section. This model consisted of transparent material (perspex) so that the air flow in the model could be made visible with smoke. The model was placed on a circular disk in the bottom of the wind tunnel. This disk could be rotated so that the inflow direction of the model could be varied.

The wind tunnel measured 1.1 x 1.1 m^2 in cross section, the wind velocity could be varied from 0 to 10 m/s. One of the side walls of the model had a square or a rectangular opening allowing exchange between the inside and the outside air.

The turbulence of the wind was simulated using laths in a zigzag pattern according to Jensen's method [1] in [5] it is described in detail how the atmospheric turbulence in a wind tunnel can be simulated.

The ventilation rate in the model was determined by the tracer gas method using N_20 as a tracer gas.

3. The Phenomenon of Turbulent Air Exchange Through an Opening

The inflow and outflow of air through an opening in an enclosed space has been studied by making the turbulent flow in the window opening visible with smoke.

Turbulences cause simultaneous positive and negative pressure differences in the window plane in relation to the pressure at the inside. These pressure differences change in place and time. The ventilation occurs by simultaneous inflow and outflow of air caused by the pressure differences. Figure 1 shows the air flow in a simplified way.

The turbulences in the window opening are caused by passing eddies rotating in alternating directions. These eddies are generated by the building or, in our case, by the model and the environment.

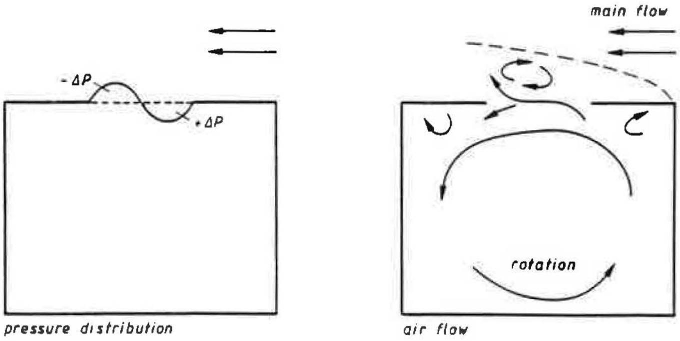

Figure 1a: Flow through the window opening at time t_1

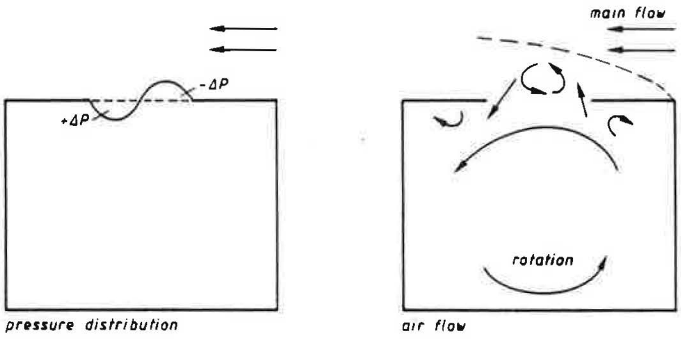

Figure 1B: Flow through the window opening at t_2

4. Factors Influencing the Ventilation Through One Single Opening

4.1. Wind Velocity

In Figure 2 the ventilation is plotted against the air velocity in the wind tunnel [2].

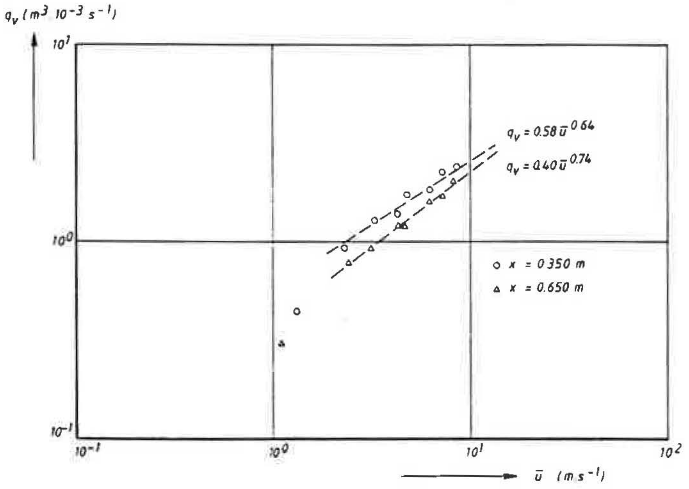

Figure 2: Ventilation against average wind velocity

We worked with two lengths upstream of the opening: 0.35 m and 0.65 m. The air flows parallel to the window opening. The following relation has been found between the ventilation and the average air velocity:

- upstream length 0.35 m: $q_v = 0.58\ \bar{u}^{0.64}$ ($\bar{u}$ in m/s, q_v in dm^3/s).
- upstream length 0.65 m: $q_v = 0.40\bar{u}^{0.74}$.

With the smaller length the ventilation is stronger because the eddies and the turbulence are more intense than with the larger length. This result is different from Bot's findings in ventilation measurements in glass houses [3]. He found that the ventilation is directly proportional to the wind velocity. In our measurements probably the scale effect plays a role, namely the fact that the air inside the model is brought in a rotating motion by the outside air flow. This rotating motion is rather strong in our case because the walls of the model are smooth at the inside.

4.2 Wind Direction

Figure 3 shows the ventilation as a function of the wind direction.

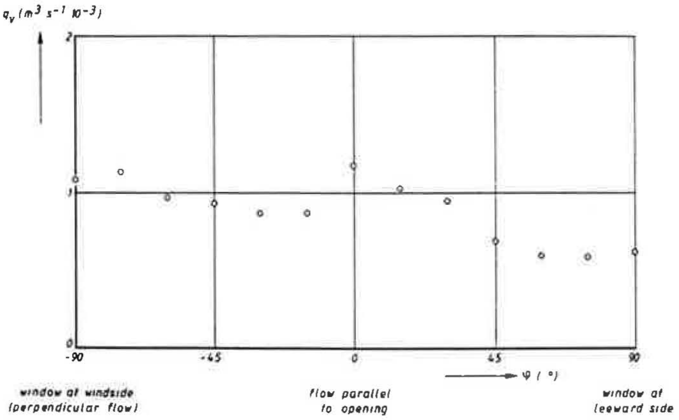

Figure 3: Ventilation as a function of the wind direction

If the flow is parallel to the window (=0°), ventilation is at a maximum. When the façade is turned from the wind the ventilation decreases gradually. If exceeds 60° there is a lee area and ventilation is at a minimum. If the façade is turned towards the wind ventilation first decreases fast because the air flow along the opening becomes more stable and the intensity of the turbulence (eddies) decreases. Turning the façade further towards the wind an area of overpressure is created. The ventilation attains a maximum for = −75° when the turbulence is somewhat stronger than if the inflow of the air is perpendicular to the façade. It should be taken into account that the fluctuations in the wind direction are smaller than in reality because of the side walls of the wind tunnel.

4.3 Building Variables

The influence of the model length upstream of the façade and the influence of the roughness of the façade on the ventilation have also been investigated. It appears that small roughnesses of the façade have no influence on the ventilation. Large roughnesses, at the size of the window opening, can cause eddies which influence the ventilation.

Figure 4 shows the influence of the façade length in the upstream direction on the ventilation. With a small façade length, ventilation is strongest because the influence of the eddies generated at the head façade is largest. From figure 4 it appears that this eddy extends to 1 metre along the façade. After that the air flow adheres to the façade again. This is illustrated in Figure 5.

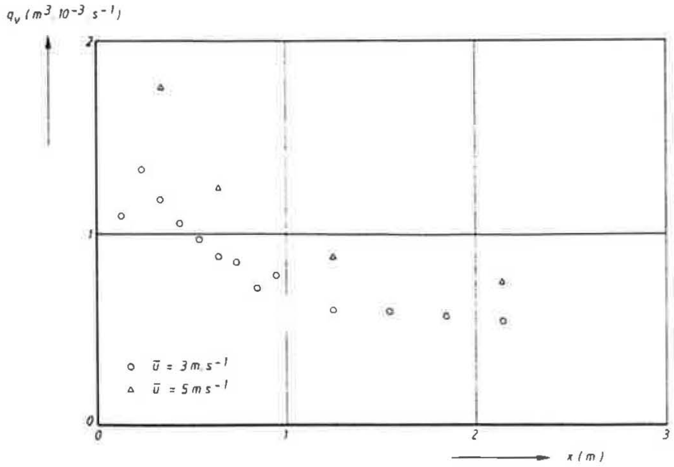

Figure 4: Ventilation as a function of the façade length upstream

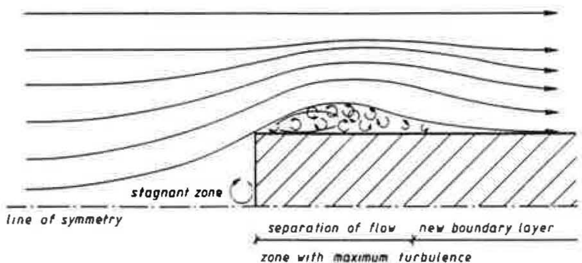

Figure 5: Flow pattern along the building with the mainflow parallel to the window wall (view from above)

4.4. Window Size

Measurements have been made at a window area varying from 0.0019 to 0.0225 m^2 and an aspect ratio (width to height ratio) between 0.16 and 6. The air velocity in the wind tunnel was invariably 3 m/s. Figure 6 gives the results of the measurements.

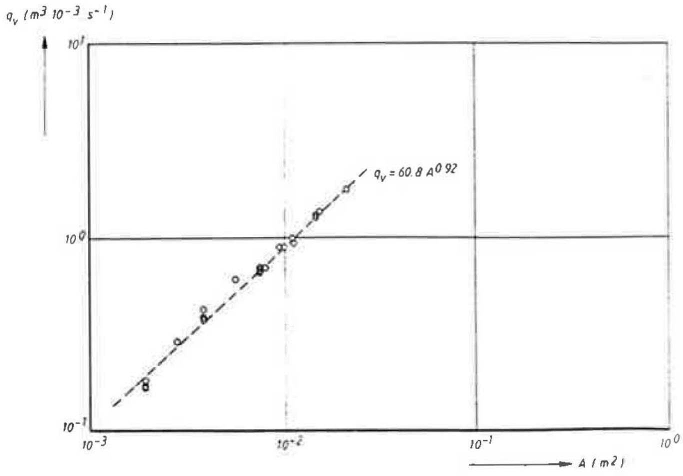

Figure 6: Ventilation as a function of the window size

The following relation is found between ventilation and window size:

$q_v = 60.8.A^{0.92}$ (q_v in dm^3/s, A in m^2).

It is seen that the ventilation is not exactly proportional to the window opening, but somewhat less. The aspect ratio apparently has no influence on the ventilation.

4.5. Window Vanes

Window vanes were simulated by plates at the size of the window opening fixed by hinges at one side of the window opening. The ventilation through the window depends on the angle of opening of the window vanes and the flow direction.

Measurements were taken at three positions of the vane; see Figure 7.

- with the hinges in a horizontal position;
- with the hinges in a vertical position, opening at the wind side;
- with the hinges in a vertical position, opening at the lee side.

As can be aspected ventilation is strongest in the second case. The results agree with those found by Warren [4].

Figure 7: Ventilation against the window vane angle for different kinds of window vanes

5. Dimensionless Ventilation

Because ventilation increases nearly proportionally to the wind velocity and the wind opening it is easy, in practice, to define a dimensionless ventilation:

$$F = \frac{q_v}{A\bar{u}}$$

In Figure 8, F is plotted against the Reynolds number which is defined as:

$$Re = \frac{A^{0.5}\,\bar{u}}{V}$$

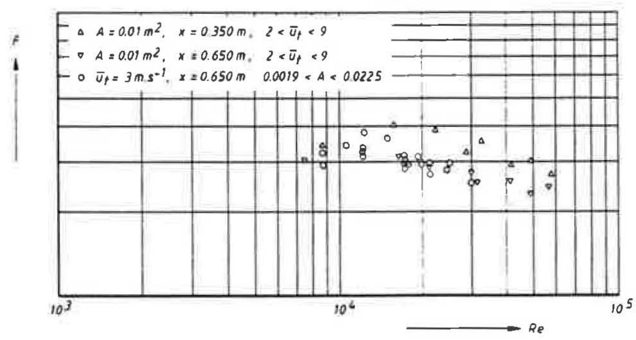

Figure 8: Dimensionless ventilation as a function of the Reynolds number

Values of F were plotted for two series of measurements, for which A = 0.01 m^2 with ū varying from 2 to 9 m/s. The upstream lengths were 0.35 and 0.65 m, respectively (see Section 4.1).

Values of F were also plotted for ū = 3 m/s with A varying from 0.0019 to 0.0225 m^2 (see Section 4.4).

Both when varying the wind velocity and when varying the window dimensions, F decreases for increasing Re numbers if Re exceeds 10^4. This is probably caused by the increasing rotation flow in the model at increasing Re numbers.

The measuring results when varying the window size suggest for $Re > 10^4$ the following relation between F and Re (see Section 4.4): $F \sim Re^{-0.16}$. The results when varying the air velocity (see Section 4.1) suggest the relations:

$F \sim Re^{-0.36}$, for an upstream length of 0.35 m;
$F \sim Re^{-0.26}$, for an upstream length of 0.65 m.

Because the range of Re is restricted in each series, there is no reason to give an empirical formula for F.

In practice, F can be considered as constant having a value of about 0.03. This applies when the direction of flow is the façade.

The values for F are about the same as those found by Warren for the model with a square opening and increased turbulence in the wind tunnel [4].

A theoretical minimum for F can be deduced from Görtler's and Reichardt's publications: $F_{min} = 0.013$.

A theoretical maximum for F can be found assuming that air enters through half the opening at a velocity ū and flows outside through the other half: $F_{max} = 0.5$.

A value of F = 0.03 indicates that the effective air velocity in a window opening is 6% of the velocity of the main flow. This applies to a flow directed along the opening. For other inflow directions the ventilation and consequently the effective velocity in the opening are lower (see Section 4.2). The ventilation attains a minimum if the opening is at the lee side. This minimum is half of the ventilation for flow along the opening. So, the effective velocity in the opening in this case is about 3% of the velocity of the main flow.

These values apply to the measurements in the cubical model. In reality, it concerns homes. The dimensions of these are much larger and their geometry is much more complicated (e.g. slating roofs). Consequently, in reality, the values found for F may be different. Therefore, values for F should be validated by field measurements.

De Gids and Phaff [6] give the following empirical formula deduced from the measurements on homes, for the ventilation through an open window:

$q_v = 0.5\,A(0.001\,u^2 + 0.0035.H.\triangle T + 0.01)^{1/2}$

where u = the meteorological wind velocity.

For isothermal ventilation the second term is 0. For a wind velocity 0 there is still a ventilation of $q_v = 0.05\,A$ due to incidental fluctuations which, in practice, always occur and cannot be simulated in a model.

For an average meteorological wind velocity of about 5 m/s, with this formula, $q_v = 0.09\,A\ m^3/s$ is found. For F = 0.03, $q_v = 0.15\,A\ m^3/s$.

6. The Relation Between Ventilation and the Pressure Fluctuations in the Window Opening

In Figure 9 the standard deviation of the pressure fluctuations from the average pressure difference between the window opening and the centre of the model is plotted against the air velocity in the wind tunnel.

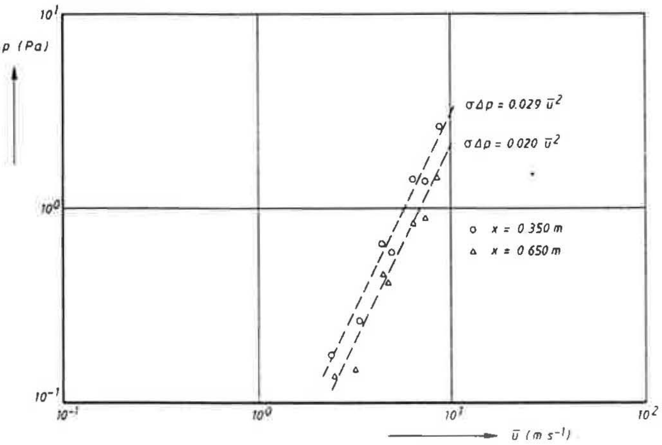

Figure 9: Standard deviation of the pressure fluctuations in the plane of the window opening against the average wind velocity at half the height of the wind tunnel

The upstream lengths of the opening were 0.35 m and 0.65 m. The pressure fluctuations, $\triangle P$, were proportional to $\bar{u}^2$, as could be expected. From the measuring results the following empirical formulas are found:

$\triangle P = 0.029\,\bar{u}^2$, for an upstream length of 0.35 m;
$\triangle P = 0.020\,\bar{u}^2$, for an upstream length of 0.65 m.

From these measurements and the ventilation measurements at different air velocities (Section 4.1) a relation can be derived between the ventilation and the pressure fluctuations [2]:

$-\ q_v = 1.80\,(\triangle P)^{0.32}$ for an upstream length of 0.35 m;
$-\ q_v = 1.72\,(\triangle P)^{0.64}$ for an upstream length of 0.65 m.

Such empirical relations are very important because with their help the rather extensive tracer gas measurements may be replaced by the much simpler pressure measurements.

7. Frequency Spectra (Open and Closed Window)

Figure 10 represents the frequency spectrum of the pressure fluctuations as a function of the wave number for an inflow length of 0.35 m. For all velocities, owing to the window, there is a sharp peak at wave numbers of 10 to 20 m^{-1}. Such a peak is a resonance peak caused by the window opening.

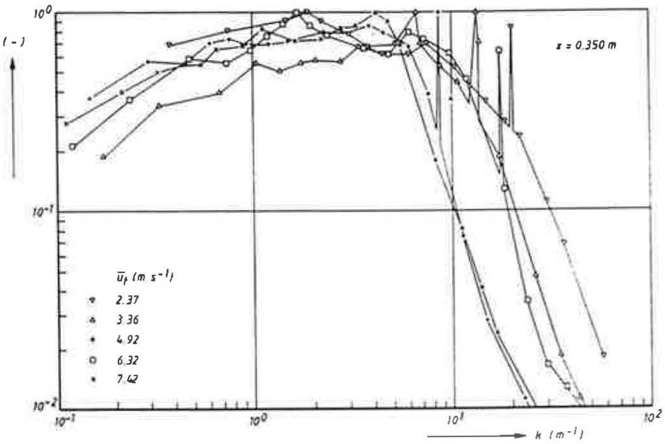

Figure 10: Spectrum of the pressure fluctuations in the plane of the window opening for an upstream façade length of 0.350 m

The turbulence spectrum is built up as follows:

$0.7 < K < 1.5\ m^{-1}$: eddies in the stagnant zone;

$2.0 < K < 5{,}0\ m^{-1}$: eddies caused by interactions between the air flow and the building (model);

$8.5 < K < 20\ m^{-1}$: eddies caused by interactions between the air flow in the boundary layer and the inside air near the window opening.

The shape of the spectrum remains about the same at increasing velocity but the energy decreases faster at higher wave numbers. Eddies caused by interactions between the air flow and the building contribute most the ventilation.

For an upstream length of 0.65 m the influence of the eddies from the stagnant zone in front of the model is much less noticable. The influence of the eddies caused by interaction between the air flow and the building on the ventilation is larger.

This explains the different exponents of ū in the relations between q_v and ū. So, the ventilation cannot only be explained from the air velocity, the window dimensions and the flow direction, but also the intensity of turbulence and the build up of the turbulence spectrum will have to be taken into account.

8. Conclusions

Considering the results of this research an estimation can be made of the ventilation through a window opening of an enclosed space. To this end the wind velocity and the wind direction must be known. The ventilation through an open window depends on the local turbulence. Therefore, for a more accurate determination of the ventilation the intensity of turbulence and the frequency spectrum must be taken into account and, besides the wind and the window dimensions also the position of the window is important.

At increasing air velocities, an increasing, rotating air motion occurs in the model which, in general, does not occur in reality. Probably, this rotating air flow results in a reduction of the ventilation.

9. List of Symbols

A	surface area of window	$[m^2]$
F	dimensionless ventilation ($F = q_v/A\bar{u}$)	[-]
K	wave number (K = frequency/$\bar{u}$)	$[m^{-1}]$
q_v	volume flow	$[m^3s^{-1}]$ of $[dm^3s^{-1}]$
Re	Reynolds number ($Re = \bar{u}l/V$)	[-]
u	velocity	$[m\ s^{-1}]$
x	upstream length of the façade	[m]
V	kinematical viscosity	$[m^2s^{-1}]$
$\triangle P$	standard deviation of the pressure fluctuation in relation to the average value	[Pa]
	angle	[°]
‾	average value	

10. References

[1] Jensen, M. and M. Franck
Model-scale tests in turbulent wind
The Danish Technical Press, Copenhagen, 1963.

[2] Vrins, E.
Ventilatie door een geopend raam als gevolg van turbulente luchtsromen
(Ventilation through an open window resulting from turbulent flows)
Thesis report, Technical University of Eindhoven, 1986.

[3] Bot, G.P.A.
Greenhouse climate: physical processes to a dynamical model
Ph.D. Thesis, Wageningen University, 1983.

[4] Warren, P.R.
Ventilation through openings on one wall only
Proc. International Centre for Heat and Mass Transfer seminar 'Energy Conservation in Heating, Cooling, and Ventilating Buildings'
Hemisphere Publishing Corporation, 1977, Washington, p.189-206.

[5] Vrins, E.
Windtunnel simulation of the atmospheric boundary layer with several terrain roughness
Thesis report, Technical University of Eindhoven, 1986.

[6] De Gids, W. and J.C. Phaff
Ventilation rates and energy consumption due to open windows
Air Infiltration Review 4 (1982), No. 1 (November), p.4-5.