UDC 725.51 : 697.052 : 53.072.1

[redacted]

comparison of internal and outside pressure distributions measured at a model and at the actual slotervaart hospital in amsterdam*

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SAMENVATTING

In het Ziekenhuis Slotervaart te Amsterdam (Nederland) zijn drukverschillen gemeten om de windinvloed te bepalen op de luchtstromingsrichtingen door de deur- en raamkieren.
De meetresultaten van de geveldrukken worden vergeleken met die van een eerder uitgevoerd windtunnelonderzoek.
De gemeten luchtstromingsrichtingen in het gebouw worden vergeleken met een eerder verricht onderzoek met een ventilatie-analogon.
Zowel het windtunnelonderzoek als het analogononderzoek blijken goed overeen te stemmen met de werkelijkheid.

* Publication no. 629 of the TNO Research Institute for Environmental Hygiene, P.O. Box 214, Delft, Netherlands.

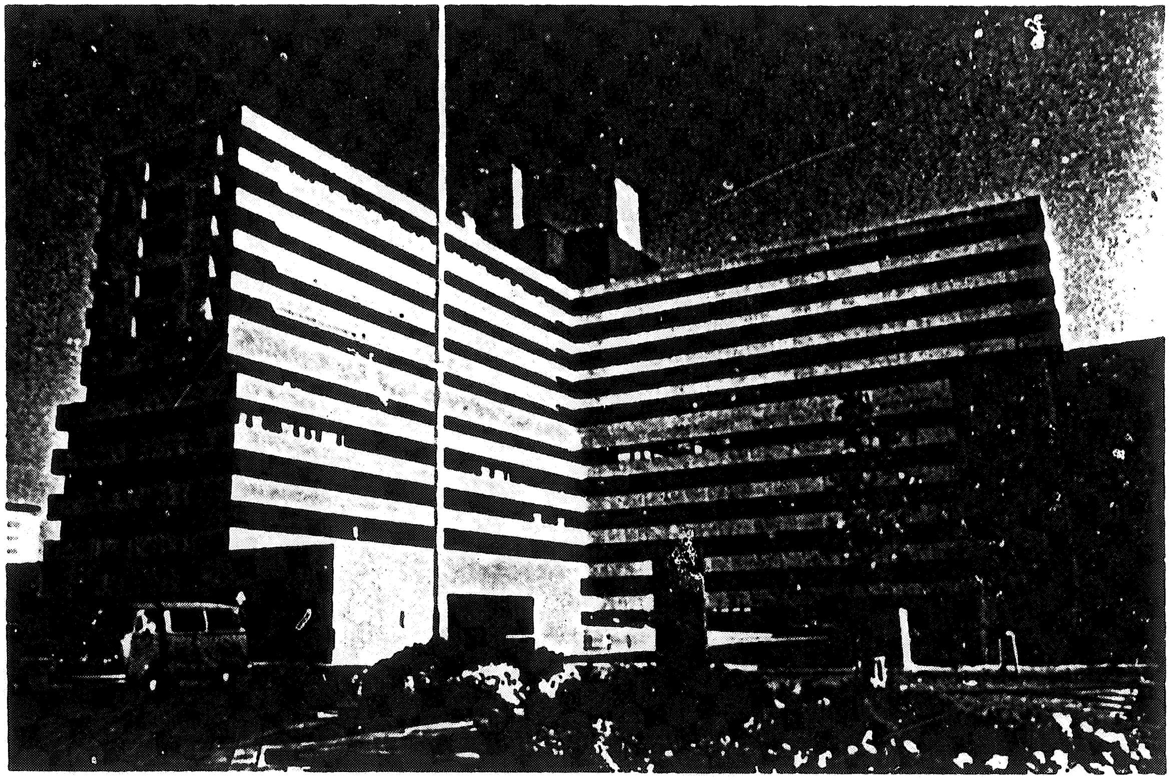
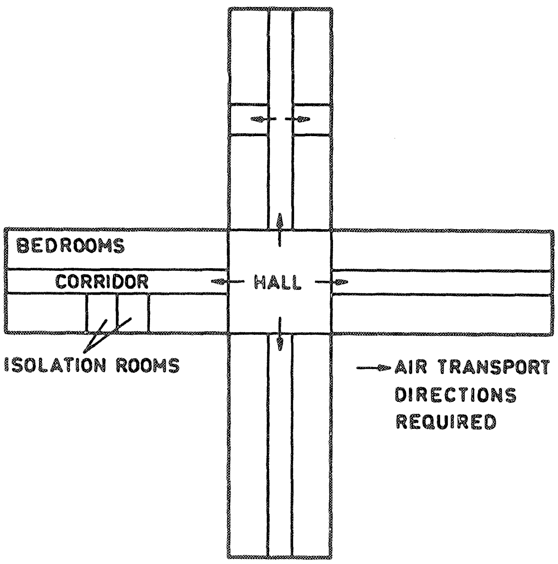


Figure 1
The Slotervaart Hospital.

Figure 2
Floor plan of a bedroom floor.



1. Introduction

For Amsterdam's Board of Works and Public Buildings the Indoor Climate Division of the TNO Research Institute for Environmental Hygiene studied, in 1969, the pressure distributions to be expected around and in the Slotervaart Hospital to be built in Amsterdam [1].

The five nursing floors (6th to 10th floors) of the hospital are built in the shape of a cross. Each of its four arms covers about 15 x 52 m. On each floor, there is a central hall on which the four arms open. The bedrooms and a lounge for the daytime are in each arm on one side of the corridor and there are rooms for various purposes on the other side of the corridor, such as isolation rooms and a ventilation room.

The aim was to indicate facilities to:

— prevent air transports between the arms of one floor;
— maintain an air flow direction from the corridors to the rooms on both sides, with the windows closed.

Figure 2 shows the floor plan of one of the nursing floors; the required air flow directions are indicated by arrows.

To underpin the advice to be supplied, electric analogue model techniques were used to study the influence of the wind on the operation of the ventilation system designed when using different kinds of doors and windows [2].

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One of the input data needed was the expected wind pressure distribution on the building. In the design stage, these pressures can only be measured in a wind-tunnel, so that complementary research on a model was necessary [3].
From the results of the measurements, alterations in the ventilating system were recommended to meet the requirements concerning the air flow directions.
The construction of the hospital was completed in 1975.

After that, the new tasks were:
- to determine the air pressure distribution around the building as a function of the wind direction, so that the measuring results of the wind-tunnel study could be tested;
- to determine the air flow directions through door and window cracks to see whether the air transport actually occur as may be expected from the analogue experiment.

This practical study was performed in 1976. The results will be discussed in the following.

2. Pressure distribution around the building
2.1 Influence of environment on wind velocity

In nature, the wind velocity tends to decrease with height. The form of this velocity profile highly depends on the number and the density of the obstacles upstream, which may be characterized by a so-called roughness factor Z_0. According to [4], from which Figure 3 has been borrowed, the so-called logarithmic law is valid for the velocity profile:

$$\frac{V_1}{V_2} = \frac{\ln Z_1 - \ln Z_0}{\ln Z_2 - \ln Z_0} \qquad (1)$$

2.2 Wind-tunnel research

Natural phenomena can be simulated in a wind-tunnel provided that the velocity profile to scale equals that in nature. This might be realized if a model of the environment would be placed in the entire starting strip of the wind-tunnel for different wind directions. Two Danish researchers, Jensen and Franck, have developed a method creating a boundary of the environment, with about the same velocity profile as that in nature. The roughness factor of the scale model of the tunnel floor must then be the same as in reality [5]. This was achieved by placing laths in the tunnel in a zigzag pattern.

The roughness factor thus obtained was $Z_0 = 13$ mm, which, in the model scale of 1 to 200, agrees with $Z = 2.6$ m in reality. We assumed this roughness to be equal for all wind directions.
Figure 4 represents the velocity profile measured in the wind-tunnel as well as the desired theoretical profile. The theoretical profile refers to the average actual wind velocities. In nature, the wind varies as to direction and

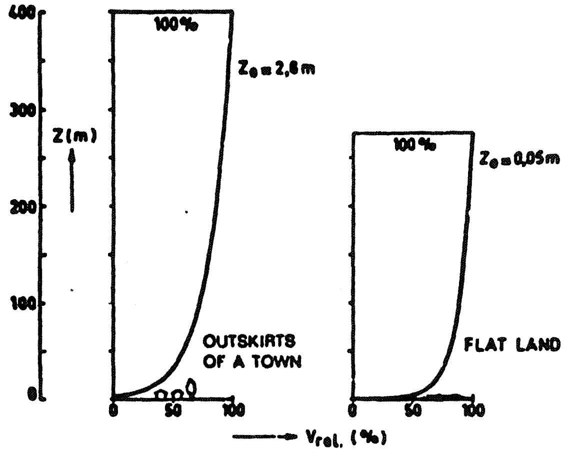
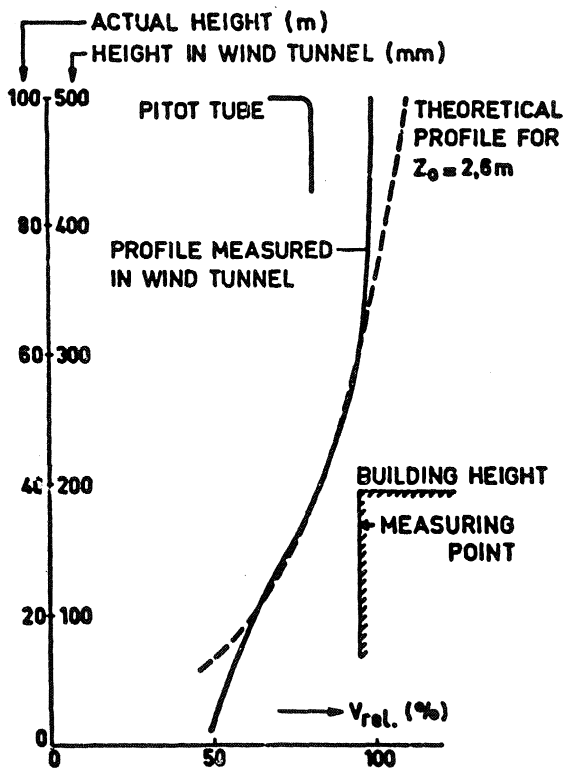


Figure 3
Wind velocity profiles for different roughnesses.

Figure 4
Velocity profile measured in the wind tunnel



force. The lower part of the velocity profile in the tunnel greatly differs from the theoretical one. This also occurs in reality because there is a strong mixing of the lower air layers caused by the proximity of the obstacles. From Figure 4 we see that the measured velocity profile in the wind-tunnel above 30 cm (which is 60 m in reality) differs from the theoretical profile. The velocity in the undisturbed air flow at half the tunnel height where the pilot tube was placed, agrees with the velocity at a real height of 70 m.
To measure the pressures on the façades, a total of 58 pressure measuring points were used in the model. The pressure levels for the eight wind directions were determined by turning the model. They were measured as pressure differences in relation to the static pressure at half the tunnel height. The dynamic pressure (propelling pressure) of the undisturbed air flow at half the tunnel height was also measured with a pitot tube.

Because the pressure levels measured in the model are dependent on the wind velocity in the tunnel, they were converted to a percentage of the propelling pressure at half the tunnel height.

2.3 Practical research

2.3.1 Working method

The pressure ratios around the building were determined by continuous recording of the pressure difference over the façades of one wing of the hospital (halfway the north wing, 9th floor).
Tht measuring period ran from 14th May 1976 to 20th June, 1976. In this period, all wind directions occurred with various wind velocities (0 up to 10 m/s).
To relate the pressure measurements to the prevailing wind velocity, copies of the wind direction and wind velocity recordings at Schiphol were sent to us by the Aircraft Meteorological Unit of the Royal Dutch Meteorological Institute. The averages per hour of the wind velocity and the wind direction were derived from these. It seemed justified to use these data for the Slotervaart Hospital because of its situation near Schiphol airport. The dynamic pressure at a height of 70 m on the location of the hospital was derived from the wind velocity measurements at a height of 10 m at Schiphol to compare the actual wind pressures with those in the wind-tunnel.
Equation (1), according to [4], applies to a height up to 275 m (see Figure 3) for flat land without buildings, among which the surroundings of Schiphol may be counted. The wind above such country may be considered undisturbed. The equation applies to 400 m, however, for the outskirts of a town, among which the surroundings of the hospital may be counted.
We see, from Figure 3, that the wind velocity at both heights may be expected equal above Schiphol and the hospital. The velocity at a height of 70 m on the location of the hospital can now be calculated from the wind velocity measurements at Schiphol, with the aid of equation (1). The roughness factor used for the hospital was $Z_0 = 2.6$ m, whereas those factors for Schiphol varied with the wind direction.
These were sent to us by the Royal Dutch Meteorological Institute, De Bilt [6]. The propelling pressure at a height of 70 m on the location of the hospital was calculated with:

$$\Delta p_{70} = \tfrac{1}{2}\rho_a(v_{70})^2 \qquad (2)$$

2.3.2 Measuring method

Before the windows, about half-way the length of the north wind façade orientation East-West on the ninth floor, wooden shutters with five pressure points were placed (see Figure 5).
The average pressure of these pressure points represented the façade pressure value. The pressure difference between the façades was measured continuously and the the momentary value was recorded on tape once every 20 seconds.

The measurements were processed by a computer, with which averages per hour of the pressure differences between the façades with their standard deviations were determined. Averages per hour of wind directions and wind velocities were taken from recording strips from Schiphol and put on tape. The wind directions were rounded off at multiples of 22.5° and the wind velocity at 0.5 m/s. The averages per hour of the pressures measured were sorted by wind direction and wind velocity. The relationship between the averages per hour of the measured pressure differences and squared wind velocities at Schiphol was then derived for each wind direction by statistical processing according to the relationship:

$$\Delta p = m(V_{Schiphol})^2 + b. \qquad (3)$$

2.3. Measuring results

Figures 6 and 7 illustrate the regression lines for south and west wind obtained with equation (3). The propelling pressure at a height of 70 m on the location of the hospital

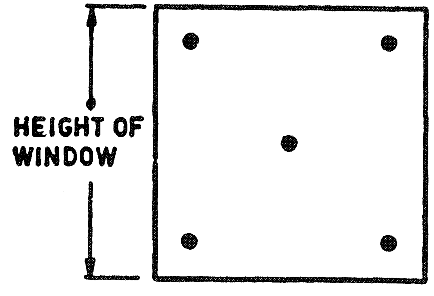


Figure 5
Wooden partition for pressure measurements.

was calculated for a wind velocity of 8 m/s, using (2) and (3). The pressure differences with this wind velocity were derived from the regression lines for each of the sixteen wind directions.
In Figure 8, the pressure difference over the north wind is expressed in a percentage of the propelling pressure at a height of 70 m as a function of the wind direction. The crosses represent the pressure differences found in the wind-tunnel examination. The number of hours of occurrence for the various wind directions is expressed as a function of the wind direction in Figure 9.

2.4 Conclusions

(a) The regression lines obtained show that a reasonably exact square-relationship between the pressure difference over the wings and the wind velocity can be derived from the averages per hour.

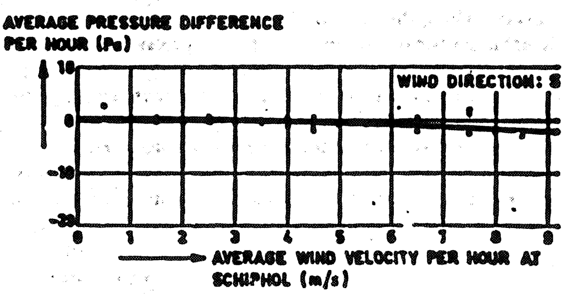
(b) Figure 8 shows that a very good agreement exists between wind-tunnel examination and reality.

(c) The wind pressures with west wind were found to be higher in the actual measurements than in those in the wind-tunnel, and lower with east wind.
This may be explained as follows:
In the wind-tunnel examination, the roughness was assumed the same for all wind directions, based on an average degree of building around the hospital. On the west side, there are lower buildings in the form of stores. On the east side, however, there are many high buildings up to near the hospital. So, west wind encounters less roughness than was assumed in the model experiment and east wind a greater roughness.

(d) With north-east wind, a greater pressure difference was found than might be expected from the wind-tunnel examination. This may be explained by the high building of the Anthonie van Leeuwenhoek Hospital which is situated at a short distance, to the NNE. So, a lighter wind charge may be expected with NNE wind and a stronger one with N and NE winds.

(e) With NW wind, lower pressures were found in reality than might be expected from the wind-tunnel examination. This is caused by the presence of buildings near the blood transfusion centre.

Figure 6
Relationship between the pressure difference measured and the wind velocity at Schiphol with south wind.



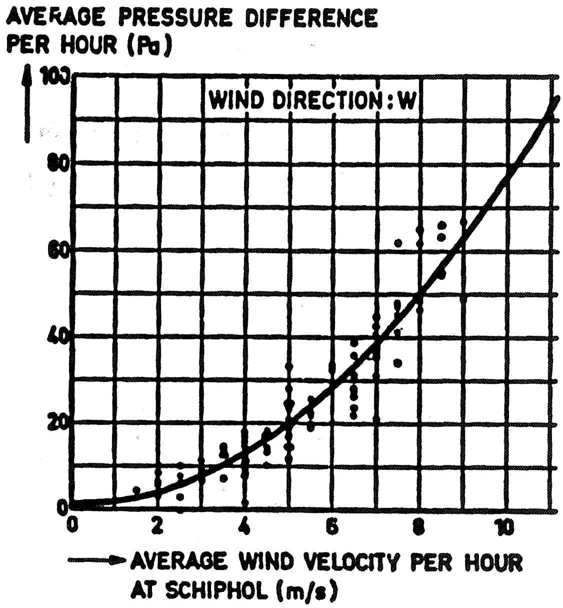


Figure 7 Relationship between the pressure difference measured and the wind velocity at Schiphol with west wind.

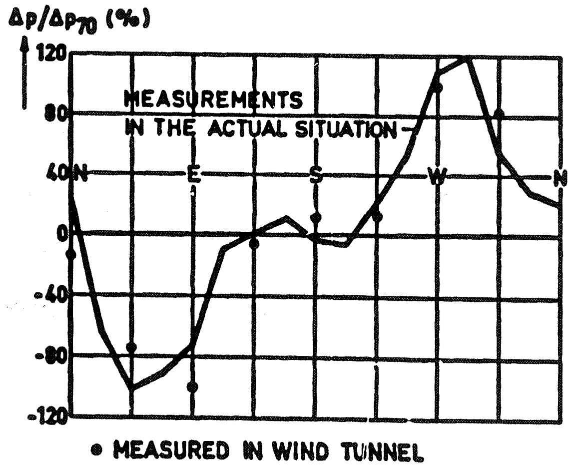
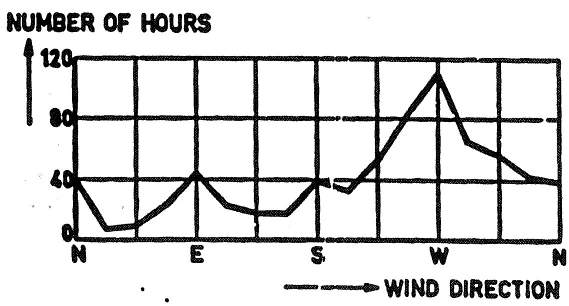


Figure 8 Pressure difference measured as a function of wind direction.
Figure 9 Number of hours per wind direction



3. Pressure distribution inside the building

3.1 Description of the ventilating system

Considering the results of the analogue research, the ventilation system was designed as follows:
On each wing and on each floor fresh air is introduced from the façade into the ventilating room. The conditioned air is led to the rooms and the corridor through two separate horizontal ducts.
One duct serves for air transport to the bedrooms and the lounge, the other for the corridor and the other rooms.
The air of the rooms which lie one on top of an other is removed to the roof via vertical shafts.
Air transport from the corridor to the rooms is achieved by removing more air per room than supplying it. The difference is supplied from the corridor through a ventilating crack under the door.
To prevent air transports between the arms on one floor, connecting doors are used combined with a ventilating system for the central hall by supplying more air than removing it.
This brings about an air transport from the hall via the connecting doors to the wing corridors.
The suction grille for the outdoor air supply to the halls is situated on the south side of a roof construction; (partial) removal of the air takes place to the roof.
By supplying more air per installation than removing it, an overpressure will result in the entire hospital; this causes, at least with calm weather, an air transport through the window cracks.
To limit the wind influence on the size of the air transports, fans with a rather large capacity are used (high-pressure system). In the analogue examination, a façade construction with fixed windows was used, whereas movable windows were used in the actual situation. Therefore, a comparison will not be quite correct.

3.2 The measurements

To determine the direction of the air-flows through doors and windows, the pressure differences on these doors and windows were measured. From the pressure differences measured and the dimensions of the door cracks, a global estimation of the air transports through the doors can be made.

The measurements can be divided into two parts:

- determination of the air-flow directions through the doors and windows on one floor of the wings;
- determination of the air-flow directions through the hall doors on the bedroom floors.

3.2.1 Determination of the air flow directions through the doors and windows on one floor, in one of the wings

3.2.1.1 *Measurement*

A whole, not yet used arm on the ninth floor of the north wing was made available by the employer for determination of the air-flow directions through the doors and windows of the sick-rooms.
Two rooms facing each other about halfway the corridor in this arm were chosen as measuring rooms to determine the pressure differences on the doors and windows. These rooms are a six-bed room (on the west side), and an isolation room (on the east side). Pressure differences on the doors and windows of both rooms were measured at rather high wind velocities with different wind directions and practically calm weather.
Inductive pressure difference meters were used and their output signals were recorded with a six-line writer.
To deal with the results of the analogue examination [2], the measurements were made first with doors and windows in the whole arm closed. Because, in practice, the doors and windows will mostly be partly opened, measurements were also carried out with some doors and windows open. The most unfavourable situation will be when only doors and windows on one façade are open, either on the weather-side or on the lee-side. Then, the pressure level in the corridor is determined for the greater part by the pressure on that façade, which causes a strong disturbance of the desired air-flow directions through the doors of the measuring rooms.
Another unfavourable situation may occur, when in a room adjacent to the measuring room, only the window is opened. The desired pressure level in the measuring room may then be disturbed via the joint air supply channel.
To determine whether the desired air-flow directions through the doors of the measuring rooms were main-

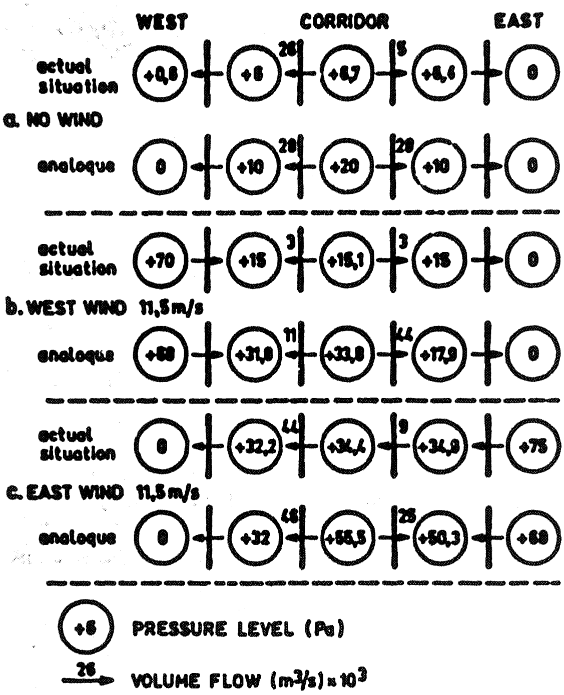


Figure 10
Measuring results on the 9h floor in north wing with closed windows.

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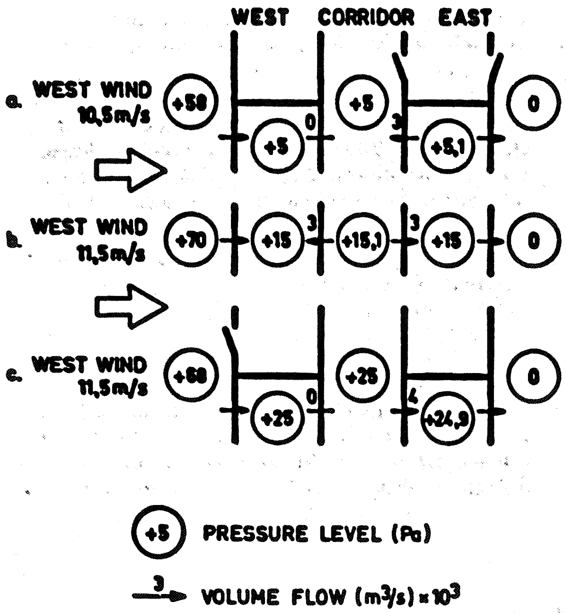


Figure 11
Measuring results on the 9th floor of the north wing with open windows.

tained in all these circumstances, measurements were carried out either with only a window or with a door and a window in one of the adjacent rooms of the measuring rooms in open condition.

3.2.1.2 *Measuring results*

Because the air system as well as the measuring instruments used may be considered as practically without any inertia, the momentary pressure distribution may be regarded as the starting situation. With strong west and east winds, moments were chosen at which the pressure differences on the façades were practically equal to the values used in the analogue (corresponding with a wind velocity of about 11.5 m/s at a height of 70 m).
Figure 10 presents some measuring results and corresponding measurements of the analogue experiment.
With calm weather (Figure 10a), it appears that the overpressure in the rooms in the wind in respect of the outside is somewhat lower than was adjusted in the analogue.
The amount of air transported from the corridor to the six-bed room corresponds with the amount in the starting situation in the analogue; the amount of air transported to the isolation room is too small, however.
The pressure difference on the doors is much smaller than in the analogue examination as a result of an air crack about 3.5 times larger under the doors. This is not essential for the operation of the air system, however, because the air transports remain practically constant in a high-pressure system.

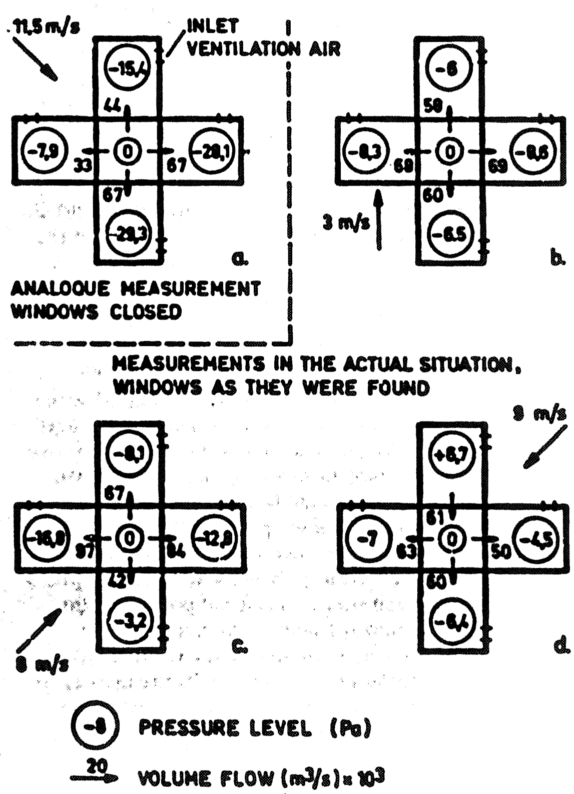
Figure 10b shows that the air-flow direction through the six-bed room door does not yet turn with west wind at a velocity of 11.5 m/s at a height of 70 m. This completely corresponds with the expectations from the analogue examination.

With a strong east wind (v_{70} = 11.5 m/s), however, it appears that the air-flow through the isolation room door turns around because the air transport in calm weather is too small (Figure 10c).

In Figure 11a, we see that the air-flow direction through the door of the six-bed room (all but) turns around when both the window and the door of a room adjacent to the isolation room are open with west wind (v_{70} = 10.5 m/s).

The same was experienced with an open window in an adjacent room on the west façade (see Figure 11c). This means the desired air-flow direction will be maintained when the air transports through the doors are correctly adjusted and the windows of the room under study remain closed.

Figure 12
Measuring results of the hall measurements on the 10th floor.



3.2.2 Determination of the air-flow direction through the hall doors to the bedroom floors

3.2.2.1 *Measurement*

The pressure differences on the four hall doors of each floor were measured with four inductive pressure difference-meters on each bedroom floor (sixth to tenth floors). They were continuously recorded by a six-line writer, in two situations:

- with windows partly opened in the four wings, corresponding to the actual situation;
- with closed windows in the four wings. This could not be done on all floors (1st to 10 th floors) simultaneously, for practical reasons, though it would have been in better agreement with the analogue examination.

When, in fact, the windows are closed only on one floor it may be expected that the pressure level on this floor will increase. This may bring about an increase of the air volumes carried off and an air transport via lift shafts and the like to other floors. These effects were not taken into account in the analogue examination.

3.2.2.2 *Measuring results*

The average values of the pressure differences recorded were determined. Figure 12 illustrates the measuring results in the actual situation on the tenth floor for some weather conditions. For comparison, one result of the analogue experiment is given. However, with another wind direction. The average pressure levels were determined with respect to the pressure in the hall which was assumed to be zero. The sizes of the air volumes transported were roughly estimated from the dimensions of the door cracks and the pressure differences measured.

3.3 Conclusions

1. Comparing the occurring pressure differences and air transports with the analogue results, we find that the hall doors are less air-tight than was expected in the analogue.
2. It appears that the distribution of air transports in the four wings is rather good for low wind velocities (Figure 12b). This goes for the other floors, too.
3. The desired air-flow directions are maintained with strong winds (Figures 12, c and d) except in the north wing with north-east wind. The reason for this is that only the east façade in this wing has movable windows, and the west façade has not.
   Because occupants tend to open more windows on the lee-side than on the weather-side, dependent on the wind velocity, the underpressure will become approximately alike in all wings. This is not possible in the north wing (eighth and tenth floors), however.
   Opening of one single window on the weather-side already may cause a considerable pressure increase in the whole wing through the rather large ventilation cracks under the doors and produce an air transport to the hall.
4. Proper comparison of the measuring results with closed windows on one floor with those of the analogue proved impossible. It was assumed, in the between the floors because it might be expected that model examination, that no air transports would occur the same pressure level would result on each floor.
   But when only the windows on one floor are closed, the effect mentioned in section 3.2.2.1 will occur influencing the air volume flows through the hall doors.
5. Often, the hall doors were opened for a short time during the measurements to let people pass. Because the doors were operated mechanically, they always opened entirely and remained open for a certain time (about 20 seconds). Thus, it was possible to conclude from the measuring results what its influence is on the transport directions. It appeared that there was some pertinent effect when the windows were closed. In the actual practical situation, however, the degree of disturbance depends on the size of the pressure difference which must be settled when the door is opened and on the number of open windows in that wing.

4. Final conclusion

It may be concluded that the model examination has stood the test of practice both in the wind-tunnel examination and in the analogue examination.

5. References

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6. Nomenclature

b	constant (see eq. (3))	(Pa)
m	constant (see eq. (3))	(kg/m)
Δp	pressure difference	(Pa)
v	air velocity	(m/s)
z	height	(m)
z_0	roughness parameter	(m)
ρ_a	density of air	(kg/m^3)

Condensed discussion

Theil: Why is often only the north-south or the east-west pressure difference measured, which, in diametrically opposed façades? The pressure difference between two façades with a relative position of 90° may likewise have much influence on the expected air-flow directions in the building.

Answer: That is correct, it must be ascertained first which façade pressures may be of importance for the investigation concerned and these must be measured. In the floorplan there are only façade openings in rooms situated on either side of a corridor. Consequently, the wind pressures on the head façades were not measures because they do not affect the ventilating system.

Stein: Did you take measurements with open windows on both sides of a corridor system?

Answer: Yes, we did. The pressure in the corridor then adjusts itself to a value lying between the two façade pressures.
The pressure level in the corridor may be compared with that in a situation that all windows are closed. The desired pressure level will be disturbed most if the windows are only opened on one side of the corridor. Therefore, we only showed this extreme situation.

Brandsma: How are the volume flows determined in practice?

Answer: Our research was aimed at determining the flow directions through door and wind slits, and not at finding the dimensions of the volume flows. To determine the flow directions, so-called inductive pressure difference meters were used; they are very sensitive and practically without inertness. The flow directions could be derived from the pressure differences measured over doors and windows. If one also wants to derive the dimensions of the volume flows from the measured pressure differences, one must know the C-values of doors and windows. We found that the C-values could easily be calculated for the doors only, because these had clearly measurable slits. The volume flows through the door slits roughly calculated in this way are indicated in the floorplans.

Bosch: It appears from Figure 11c that the flow direction through the door with a wind velocity of 11.5 m/s just does not reverse if the window of the adjacent room is open. In Figure 12d, however, we see a similar situation. For you said that the windows on the east façade were open and those on the west side could not be opened. Now it seems to be all wrong because the air-flow is directed to the hall. How can these two conditions be made to agree.

Answer: We have seen that opening of windows only causes an increase of the pressure level on the weather-side in the corridor of the wing concerned (see Figure 11c). It appears that this pressure increase just does not disturb the desired flow direction from the corridor to the room. However, there will be an air volume flow wit increased pressure from this wing to the hall where the pressure level is lower. Therefore, Figures 11c and 12d agree.

Frielink: In your paper you advised that after all movable windows should be placed in the north façade of the tenth floor. Is this the only solution?

Answer: In the wing in question movable windows were only placed in the east façade and in the west one.
In the other wings, however, movable windows are provided on both sides. The pressure level that in a corridor adjusts itself lies between both façade pressures when the windows on both sides of the corridor are open. If often lies nearer the lee-side pressure, however, because the users tend to open windows more frequently on the lee- than on the weather-side. This effect did not occur in the wing concerned because the windows could not be opened on the lee-side.
There are two possibilities: either movable windows in both façades or, if this is not possible, closed windows in both façades.
In the latter case, an average pressure level in the corridor will adjust itself. However, it will be a little higher than that in the other wings.