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WIND TUNNEL AND ON-SITE PRESSURE DISTRIBUTION MEASUREMENTS ON A HOUSE AND ITS EFFECTS ON INFILTRATION

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1. INTRODUCTION

Infiltration in buildings is a process which is not well understood. Since J.B. Dick [1, 2, 3] studied this infiltration in the 1950's there was not much progress until 1975 in this research field.
Energy crises in the last decade causes almost everyone in the world to pay attention to infiltration of buildings.
Speculative figures appear in literature about energy losses due to infiltration and few measured figures were available.
An enormous amount of questions arise, for example:

- Can we predict infiltration with models and with what accuracy?
- Have we enough suitable information for these models?
- Is there any information about pressure distribution on real buildings which is usable for existing prediction models?
- Are the available figures about air leakage coefficients of our building envelopes respresentive for our present buildings?
- What is the infiltration rate in existing and occupied buildings?
- What is the occupancy effect on infiltration etc.?

Many investigations were started to give answers to the above-mentioned questions. Giving all answers in a reasonable time, which may lead to good policy-measure for authorities was impossible. So coordination in this field started in April 1978, when investigators from several parts of the world discussed infiltration's problems and needs in an International Energy Agency meeting at Paris. It seems to be successful for future investigations [4].
Nevertheless, one of the problems in studying infiltration was the difficulty in measuring pressure distribution on real buildings before accurate and usable electronic pressure transducers became available.
Also, before 1970, recording and processing such data was a limitating factor, as was measuring pressure distribution on site. This paper is a continuation of publication 620 of the Research Institute for Environmental Hygiene TNO, September 1977 [5].

2. PRESSURE DISTRIBUTION

2.1 General

The pressure distribution on a building can be seen as a result of a collection of pressure difference measurements for several facades or areas e.g. roof or roof areas against the variable wind direction [6].

2.1.1. Pressure Differences Due To Wind

If a building is located in a particular situation, the wind causes pressure differences. This wind pressure distribution will depend on the interrelationship between the wind velocity, wind direction and exposure, and the form and situation of the building.

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It can be expressed as:

$$\Delta p_i = Ki.\ 1/2\ \rho.v^2 \qquad (1)$$

where

Δp_i = pressure difference across and external wall or roof [Pa]

Ki = dimensionless pressure coefficient depending on the form of the building and the exposure [-]

ρ = air density [kg/m^3]

v = wind velocity [m/s]

For each wind direction, there are different pressure differences across different walls, e.g. roof (i). In this study, the minimum wind direction step is 10^o.

2.1.2. Influence Of Environment On Wind-Velocity

In nature, the wind velocity tends to ~~decrease~~ increase / [illegible] with height at least when the atmosphere is stable; for instance, when flow due to thermal effect in the boundary layer will not disturb the wind profile.
The form of this velocity profile of the boundary layer highly depends on the number and density of obstacles upstream, which may be characterized according to Wieringa [7] as:

$$\frac{v_1}{v_2} = \frac{\ln z_1 - \ln z_o}{\ln z_2 - \ln z_o} \qquad (2)$$

where

v_1 = wind velocity at height 1 [m/s]

v_2 = wind velocity at height 2 [m/s]

z_1 = height 1 [m]

z_2 = height 2 [m]

z_o = roughness parameter [m]

For an example, see Fig. 1.

2.1.3. Stack Effect

Temperature differences between inside and outside cause differences in air density and result in pressure differences. This can be expressed as:

$$\Delta p_{th} = (\rho_c - \rho_w)\ g.h. \qquad (3)$$

where

Δp_{th} = pressure difference (stack effect) [Pa]

ρ = air density [kg/m^3]

c = cold air

w = warm air

g = gravitational force [N/kg]

h = height between inlet and outlet openings [m]

2.2. Site Measurements

2.2.1. Object Of Investigation

The measurements were taken place at a building on the first row of the dunes on the North

Sea.
For the orientation and location of the building and the floor plan of the flat, see Fig. 2, 3 and 4.
The flat under study was located at the third and highest story.
The pressure differences between three walls, the outlet of the ventilation ducts, front door and inside have been measured during several months. For the location of the measuring points, see Fig. 2.

2.2.2. Measurement Devices

Electronic low-pressure differential transducers were used. Very small and fast fluctuating pressure differences of about 0,01 Pa can be measured. The pressure difference range was 0 - 140 Pa. All data were recorded with an incremental data recorder and off-line processed with a computer.

2.2.3. Results

For each hour the mean pressure difference is calculated from 30 - 75 samples. In most cases the number of samples was 60. The mean hourly values measured at wind velocities of 4 m/s and higher were divided by the pressure head of the wind on 10 m at the Hook of Holland Meteorological Station. This station has about the same position to the coastline as the flat. The distance between the flat and meteorological station is about 15 km.
From the resulting dimensionless pressure (NW-SE. SW-SE, roof-SE) differences, the mean value of several hours for each direction was determined and plotted against wind direction. See Fig. 5, 6 and 7 (solid lines).
Scale model measurements in the wind tunnel do not allow measurements between inside and the facades and the facade and the front door. For this reason, these pressure differences will not be discussed.

2.2.4. Remarks

From the figures it can be seen that:

- The mean dimensionless pressure differences vary strongly, at least with wind directions between 180° and 240° from -1.4 to about +2.
- The standard deviation in some cases is about 0.8 in the most steep parts of the curves, and 0.4 in the flat parts of the curves.
- For the wind directions 40°, 50°, 170°, 310°, 330°, 340° and 350°, no measured data were collected. During the measurements, the wind did not blow from these directions.

2.2.5. Discussion

The large standard deviation can be explained by the following items.

. Turbulence effects [8]

Turbulence effects cause rapid fluctuations in the velocity over a wide range of frequencies and amplitudes, and therefore on pressure differences.

. Instability of the boundary layer.

Some weather types are extremely unstable, and consequently the increase of mean wind velocity with height is very small [8].
Real stable boundary layer situations only occur early in the morning and in the evening. During the day, due to the sun, there is a warm ground surface and therefore, an upgoing vertical heat flow. During the night there is, due to radiance effects, a cool ground surface and therefore, a vertical downflow of heat. In the case of an upgoing vertical heat flow the mechanical turbulence due to the nature of wind and obstacles will be increased by a convective term. During the night the mechanical turbulence will be decreased by a convective term [9]. Turbulence will increase pressure differences. Because the measurements took place during the 24 hours of a day this instability of atmosphere will have influence on the results.

. Temperature differences between inside and outside.

During the measurements the outside temperature varies between about -2 °C and + 27 °C. As stated before in Fig. 5, 6 and 7 the hourly values measured at wind velocities of 4 m/s and higher are plotted against wind direction. The influence of temperature difference between inside and outside is in the order of magnitude as calculated below.

$$\begin{aligned}\Delta p_{th} &= (\rho_c - \rho_w).g.h_{max} \\ &= 0.1 \;.\; 9.81.25 \\ &= 2.4 \text{ Pa}\end{aligned}$$

Hence, the influence on the dimensionless pressure differences is:

$$\frac{\Delta p_{th}}{1/2\ \rho.\ (V_{min})^2} = \frac{2.4}{9.6} = \underline{0.25}$$

. Accuracy in the measurements.

The accuracy of transducers, scanner, D.V. meter etc. as well as the number of samples for calculating mean hourly values have influence on the results.

2.3 Wind Tunnel Measurements

2.3.1. Measurement Equipment

The wind tunnel used for this investigation is of the open return type with an enclosed measurement section. The cross section is about 1.1 x 1.1 m^2.
For the measurement devices see paragraph 2.2.2.
The roughness of surroundings, apart from obstacles in an area of about 75 m, were simulated in three areas with laths and blocks upstream from the model [10].Those buildings, within a range of about 75 m, which were simulated can be seen in Fig. 8 (photograph).

2.3.2. Results

The measurements were carried out with and without roughness of the surroundings and direct obstacles.
The results can be seen in Fig. 9, 10 and 11. The solid lines are the results with roughness of the surroundings and direct obstacles. The dotted lines are the results for the building in which the flat under investigation is located, without any obstacles in the wind tunnel.

2.3.3. Remarks

- Though the curves (with and without surroundings) have about the same shape, the differences are considerable. (See Table 1.)

TABLE 1. The Effect of Roughness of the Surroundings and Direct Obstacles on the Dimensionless Pressure Differences

	Effect on dimensionless pressure difference $\frac{\Delta p}{1/2\ \rho.\ (v_1)^2}$		
	NW - SE	SW - SE	Roof - SE
Wind from:			
the city	0.5	0.5	0.5
the dunes	1.0	1.0	0.2
the sea	1.0	indistinct	
the two identical buildings upstream	0.4	0.3	0.2

- The curves seem to be shifting from each other at least in certain areas. The accuracy in the wind direction is about 10^{o}. The position of the models in the wind tunnel were again verified after the measurements. The shift in direction was less than 5^{o}.

2.3.4. Discussion

Although the shift in direction is limited, there is an influence on the resulting curves. This can be considerable in the steep parts of the curves.
The reproducibility based on the results of duplication of several measurements was about $0.15 \cdot 1/2\, \rho\, (v_{10})^2$.
The indistinctness of the effect of roughness and obstacles by wind from the sea for the (SW - SE) and (roof - SE) pressure differences can be due to the method of making a smooth but maybe a too steep transition between wind tunnel floor and model plate. The flat is situated on the first row of the dunes from the North Sea. Hence, by wind from the sea, the model plate is thicker than by wind from the city. The transition is made to overcome this difference in thickness.

2.4. Comparison Site/Windtunnel Measurements

2.4.1. Results

For comparison, see Fig. 5, 6 and 7: the solid lines are the results of the site measurements; the dotted lines are the results of the wind tunnel-measurements with roughness of the surroundings.

The correlation coefficient for the comparison of wind tunnel and site measurements of the three pressure differences can be seen in Table 2. Linear regression is assumed.

TABLE 2. The Correlation Coefficient for the Comparison of Windtunnel and Site Measurements.

pressure difference	correlation coefficient	number of directions
SW - SE	0.88	29
NW - SE	0.88	29
Roof - SE	0.68	29

For an example, see Fig. 12.

2.4.2. Remarks

From the curves and correlation coefficients can be seen that there is a reasonable agreement between wind tunnel and on-site measurements. See also Ref. [11].

In the wind tunnel the terrain roughness was changes only three times, for wind from the sea, from the dunes and from the city.
In the situation of wind from the city, the roughness probably has more variety as can be seen from the significant differences of pressures between wind directions of 80^{o} to 130^{o}.
The differences in the curves between 300^{o} and 350^{o} may be due to the few number of hours pressure data during the site-measurements.

2.4.3. Discussion

The lower correlation for the (Roof - SE wall) pressure difference might the due to:

. Location of the measurement point on site.
  This was located on top of the hood instead of in the hood.

- Thermal effects.
  Because all apparatus and devices were installed inside the flat, a tube for measuring pressure on the roof was partly outside the building.

The dimensionless pressure difference between the two parallel facades of this flat (NW – SE) has maximum values of -1.4 to +2.
The high peak value of +2 can be explaned by the shape of the building in relation to the wind direction ($240^o/250^o$).
The value of -1.4 for wind directions between 90^o - 160^o, wind from the city, agrees rather well with results from other investigators [10] [12]. One must realize that:

- the measured pressure differences are related to a pressure head at 10 m height.
- the curves give the dimensionless pressure differences between two parallel outside facades.

3. INFLUENCE OF OPENING WINDOWS

3.1. On Pressure Differences

Even opening one small ventilation window will have a large effect on pressure differences in buildings and hence on infiltration.
The air leakage value of an open window (0.8 x 0.25 m^2) is about 20 x the value of a ventilation duct and about 50 x the value of the cracks, gaps, ect., in an outside facade.
The pressure difference across the open window therefore tends to nearly zero.
In this study, the position of windows and doors (open or closed) was registrated with the aid of micro-switches. When analyzing the results, it appears that the ventilation window in the bathroom was almost constantly open except when the wind was strong and blew. from a direction between South-west and North. The effect on the pressure difference across the bathroom/kitchen wall can be seen on Fig. 13.

An open ventilation window on the leeward side of a building will increase pressure differences across the windward facades and its openings, but decrease pressure differences across natural ventilation ducts and other leeward facades. On the other hand, an open windward ventilation window will increase pressure differences across leeward facades and natural ventilation ducts, but decrease the pressure differences across other windward facades and its openings. This is one of the reasons for increasing infiltration more with opening an windward window than with opening a window on the leeward side. This can be explained by the increase in the pressure difference across the natural ventilation ducts, which have, at least in the Dutch situation, the lowest air resistance.

3.2. On Infiltration

3.2.1. Measurements

For the infiltration rate measurements the tracer gas (helium) decay method with the aid of katharometers was used. All internal doors were open during the measurements. The flat is considered to be one room with 6 katharometers (see Fig. 2). During about 9 hours, infiltration rate measurements took place with different open window situations and under different weather conditions.
The size of the small ventilation wondows is 0.8 x 0.25 m^2. They are situated about 2 m from the floor. The window vane, which pivoted horizontally, can be opened up to about 45^o.

3.2.2. Results

In Table 3 measured infiltration rate and the conditions are given.

In Table 4, open window situations are compared with closed window situations under about the same weather conditions [5].

TABLE 3

Infiltration rate h^{-1} tot.	meteo wind-velocity m/s	wind-direction o	temp. diff. in/outside K	number of windows open	leeward/L*1 windward/W*1
5	14	210	5	4	W
2.5	15	230	5	3	W
1.8	15	240	5	2	L
1.3	4	150	9	3	W
1.2	8	310	17	2	W
0.8	8	340	17	2	W
0.5	1	99*2	9	2	-*2
0.3	0.5	320	9	2	L
0.2	1	180	9	2	L

*1 windward e.g. leeward means that there is a positive c.q. negative pressure difference across the facade

*2 wind direction variable

TABLE 4

	window situation	infiltration rate (a) h^{-1}	met windvel m/s	wind direction o	temp diff. in/out K
1	all windows closed	0.6	8	290	15
	2 windward windows open	1.2	8	310	17
2	all windows closed	0.4	7	360	0
	2 windward windows open	0.8	8	350	17
3	all windows closed	1.2	11	250	7
	2 leeward windows open	1.8	15	240	5
4	3 windward windows open	2.5	15	230	5
	all windows closed	0.3	3	140	4
	3 windward windows open	1.3	4	150	9
5	all windows closed	0.1	1	99*2	9
	2 windows open	0.5	1	99*2	7
6	all windows closed	0.4	10	210	8
	4 windward windows open	5	14	210	5

3.2.3. Remarks

Opening two small ventilation windows on the windward site of the building gives, at a meteorological wind velocity of 8 m/s, an infiltration rate of about 1 [h^{-1}], boyancy effects neglected.
In the case where the boyancy effects are predominant to wind effects, a 9 K temperature difference causes an infiltration rate of about 0.3 [h^{-1}].

3.2.4. Discussion

The few number of open window measurements and the wide range of circumstances make relations between wind velocity, wind direction and temperature difference inside/outside impossible.
For comparison with other work in this field [13] [14] [15] the infiltration rates in Table 3 are inadequate. The phenomena of flow through openings in one wall is not clearly understood yet and needs further investigation [4].

3.3. Relation Of Opening Windows To Meteo-Data

3.3.1. Method

The linear regression technique was used to calculate correlation coefficients on open windows and balcony doors.
The correlation between the number of minutes a certain window or door was open and the weather conditions, wind velocity and temperature was calculated.

3.3.2. Results

In Table 5 the correlation coefficient of the relation between outside temperature, wind velocity and the number of minutes a window is open can be seen for the two most frequently used ventilation windows.
Difference is made between windows on windward and on leeward sides.

Between the brackets, there are three numbers. The first is the number of hours that the window during the measurements was located either on the windward or the leeward side. The second number is the number of full hours that the window was open. The third is the opening frequency. A positive correlation coefficient means that there is a relation between opening the window when outside temperature or wind velocity increases. These relations are calculated for the measurement hours between 6 A.M. and 12 P.M.

In Table 6 the correlation coefficient of the relation between outside temperature and the number of minutes a window or door is open can be seen for two ventilation windows and a balcony door.

A difference is made for outside temperatures above the so-called basic temperature and below that temperature.
The basic temperature for a building can be determined as the outside temperature above which heating is unnecessary.
For this flat, this temperature is 16.6 °C [16].

TABLE 5

		correlation coefficient	
		windward	leeward
Bathroom ventilation window	temperature	+ 0.12	+ 0.55
		(54, 45, 5)	(115, 75,9)
	wind velocity	+ 0.07	+ 0.20
livingroom ventilation window	temperature		+ 0.47
		(78, 0, 0)	(95,31,11)
	wind velocity		+0.05

TABLE 6

Correlation coefficients for the relation between outside temperatures < 16.6 °C and > 16.6 °C and the number of minutes a window or balcony door was open		
	outside temperature	
	< 16.6 °C	> 16.6 °C
livingroom ventilation window	+ 0.72	- 0.08
bathroom ventilation window	+ 0.41	- 0.53
kitchen balcony door	- 0.10	+ 0.46

3.3.3. Remarks

From Table 5 it can be seen that:

- The ventilation window is not used during daily hours with position on the windward side.
- Windward relations are not quite clear.
- Opening ventilation windows on the leeward side shows a beter relationship to outside temperature than to wind velocity.

From Table 6 the following remarks can be made:

- For temperatures below 16.6 °C there is a positive correlation for the small ventilation window.
- For temperatures above 16.6 °C this relationship is negative.
- The positive correlation of the balcony door for temperatures above 16.6 °C means that this door is used instead of the bathroom ventilation window on the same facade.

3.3.4. Discussion

The results of window door opening habits for this exceptionally situated flat (with the additional disadvantage of only on inhabitant) are not suitable for general use. Further investigation is neccessary [17].
Nevertheless, finding clear significant results is positive with respect to the measurement method of registrating opening windows and doors with the aid of micro-switches.

4. INFLUENCE OF TEMPERATURE DIFFERENCE ON INFILTRATION

4.1. Results

To study this influence, the thermal forces must be predominant over the wind forces. In field studies, where one is depending on weather conditions, the requirement of predominance is difficult. In our investigations it was not possible to obtain comparable results at wind velocities lower than 2 m/s.
In Table 7 the results of comparable measurements on infiltration can be seen.

TABLE 7. Influence Of Temperature Difference Inside/Outside On Infiltration

	infiltration rate a (h^{-1})	weather conditions		
		wind vel. m/s	wind direction o	temp. diff. K
1	0.22	2.5	100	0
	0.29	3.0	120	-4*
2	0.22	2.5	100	0
	0.31	3.0	140	+7
3	0.23	3.0	240	5
	0.32	3.0	300	-3*
4	0.19	2.0	100	0
	0.24	2.0	110	20
5	0.22	2.5	100	0
	0.31	2.5	100	20

* A negative temperature difference means the outside is warmer than the inside.

4.2. Remarks

From Table 7, it can be seen that:

- Due to temperature differences between 3 K to 20 K, the infiltration rate increases by 0.05-0.09 (h^{-1}), at wind velocities of about 2 - 3 m/s.
- The influence of temperature differences on infiltration is a maximum of about 30%, at wind velocities of about 2 - 3 m/s.

4.3 Discussion

For comparison, calculations were made with a simple model of the flat.
An 8 K temperature difference causes an infiltration rate of 0.1 h^{-1}. These calculations have been made with results of air leakage measurements. These measurements took place in spring. Hence, due to possible changes in air leakage the calculated values must be considered carefully.

5. CONCLUSIONS

- There is a reasonable agreement between wind tunnel and on-site pressure measurements. See Table 2.
- The influence of terrain roughness and surrounding buildings may change the pressure difference between two facades up to 1.0 x 1/2 $\rho . v^2$ (See Fig. 9,10,11).
- Two small open windows on the windward side increase the infiltration rate by a factor 2. See Tables 3 and 4.
- Smaller ventilation openings will be used more frequently than, for instances, balcony doors at temperatures lower than the so-called basic temperature. See Table 6.
- Temperature relations give better correlation than wind relations in the case of opening ventilation windows. See Table 5.
- A 20 K temperature difference between inside and outside causes an infiltration rate in

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this flat of about 0.1 h^{-1} at wind velocities of 2 m/s.

6. NOMENCLATURE

Δp	pressure difference	[Pa]
ρ	air density	[kg/m^3]
v	wind velocity	[m/s]
K	dimensionless pressure coefficient	[-]
z	height (roughness)	[m]
g	gravitational force	[N/kg]
h	height	[m]
a	infiltration rate	[h^{-1}]
r	correlation coefficient	[-]
ΔT	temperature difference	[K]
α	wind direction	[^{o}]
q_v	volume flow rate	[m^3/s]
t	temperature	[^oC]

Subscripts

1,2....	Z_1, Z_2, height 1, height 2
i	unknown numbers of variables
c	cold air
w	warm air
th	thermal (stack effect)
o	Z_o roughness parameter at height 0 m
max	maximum
min	minimum
10	v_{10}, velocity at height 10 m
meteo	meteorological
tot.	total
calc.	calculated

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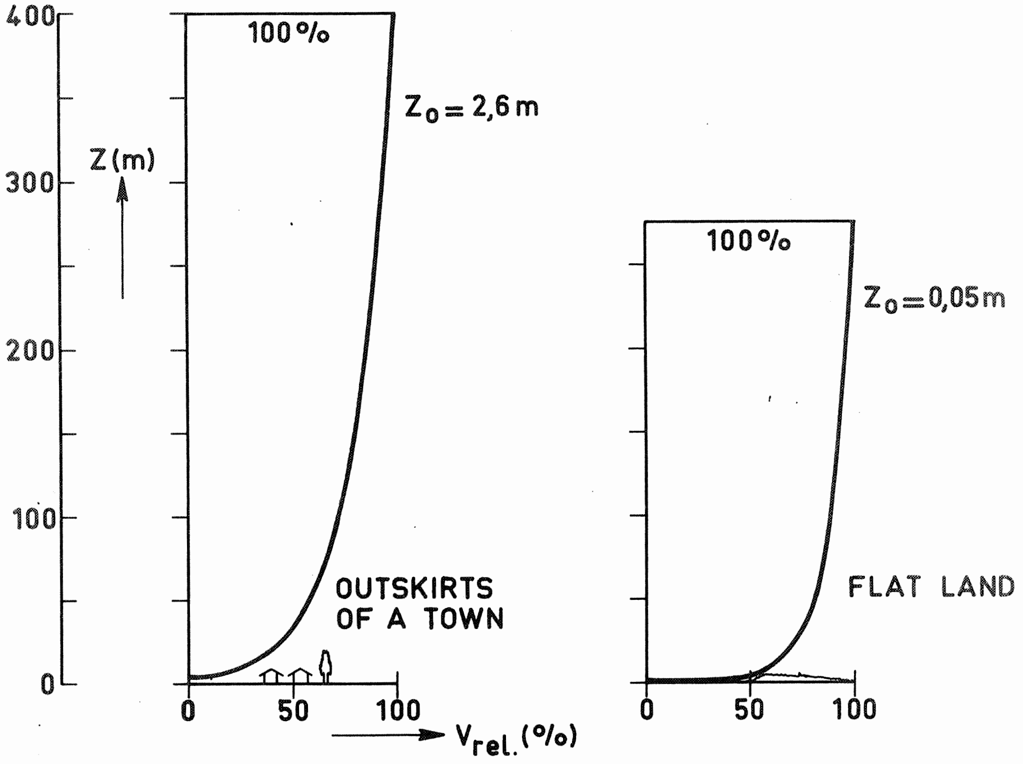


Fig. 1 An example of velocity profile of the boundary layer

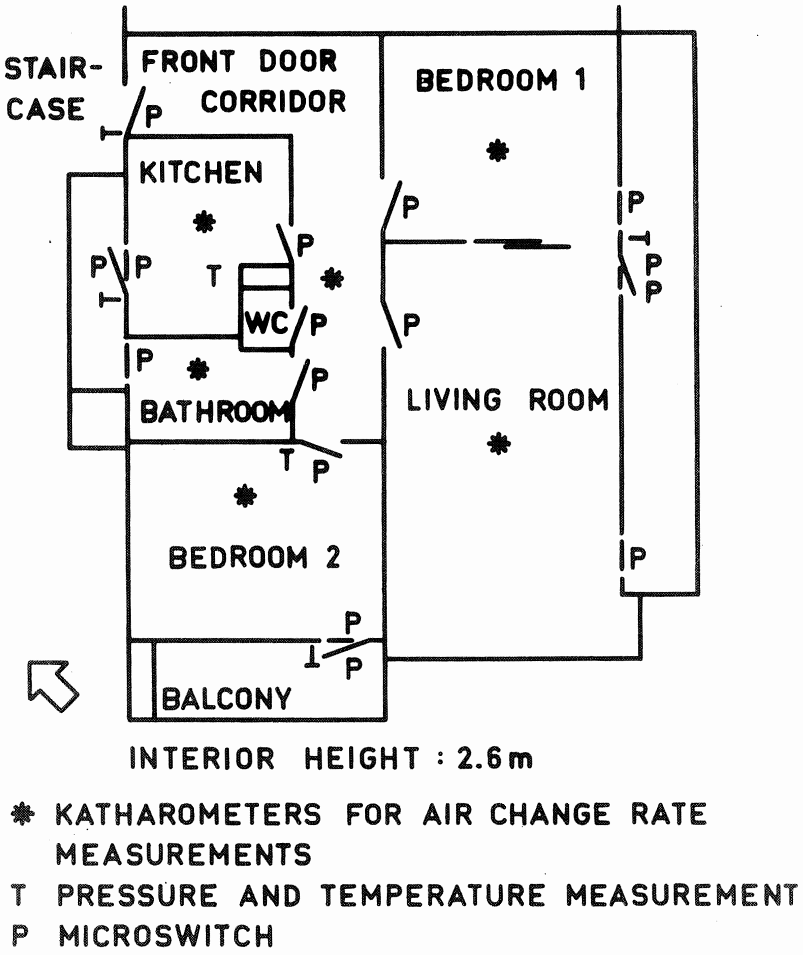
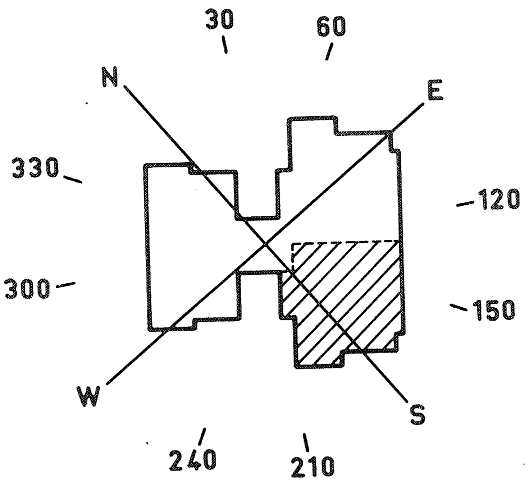
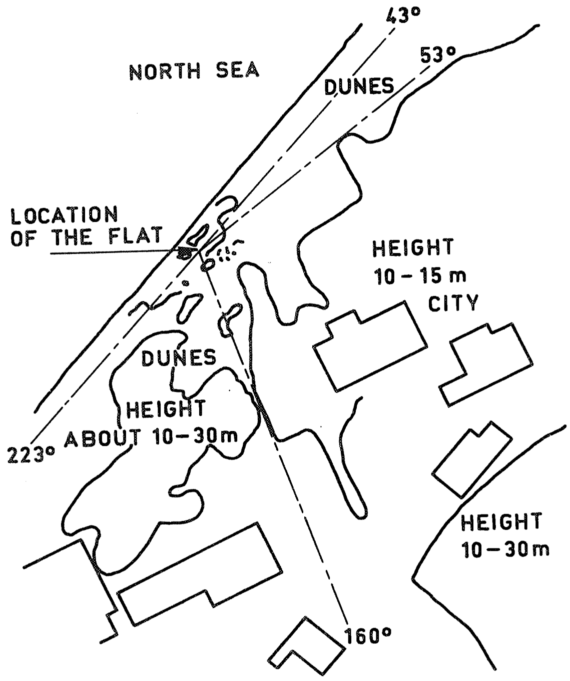


Fig. 2 Floor plan of the flat



POSITION OF THE BUILDING

Fig. 3



LOCATION OF THE BUILDING

Fig. 4

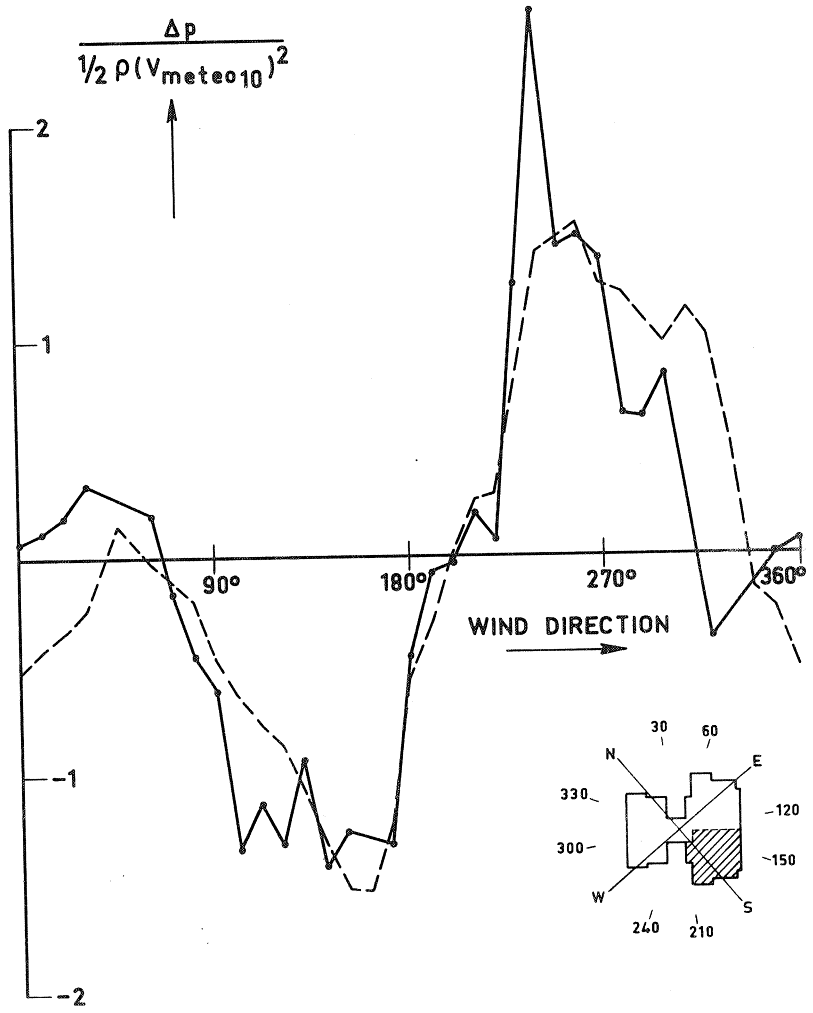
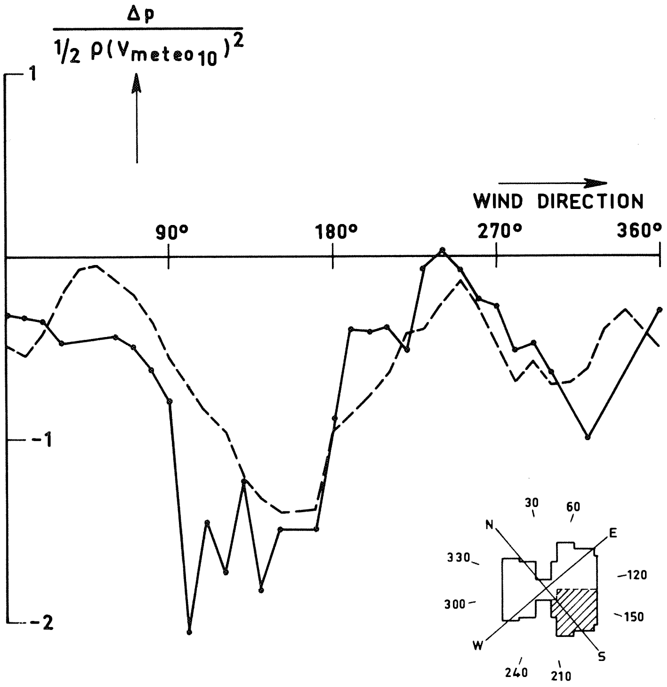


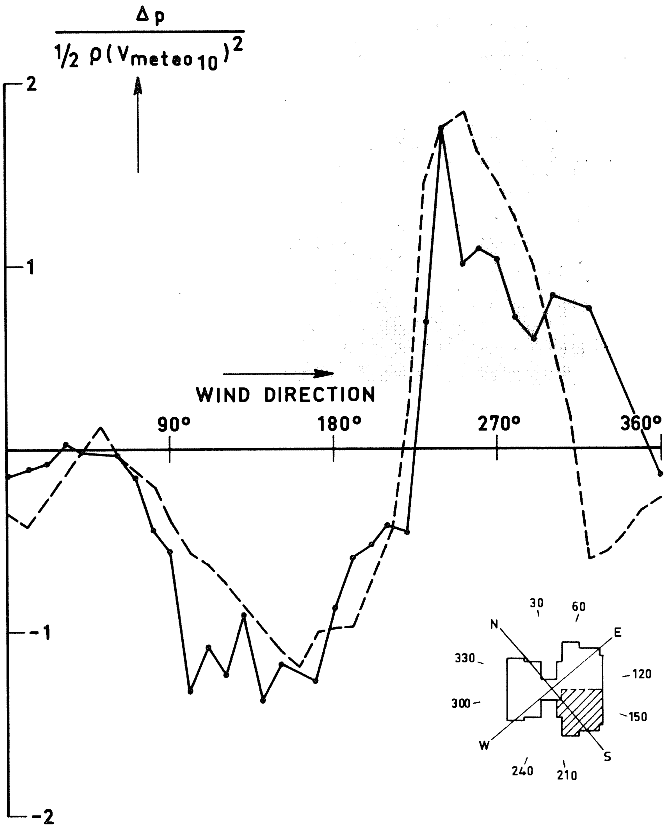
Fig. 5

PRESSURE DIFFERENCES SW-SE WALL



PRESSURE DIFFERENCE ROOF - SE WALL

Fig. 6



PRESSURE DIFFERENCES NW-SE WALL

Fig. 7

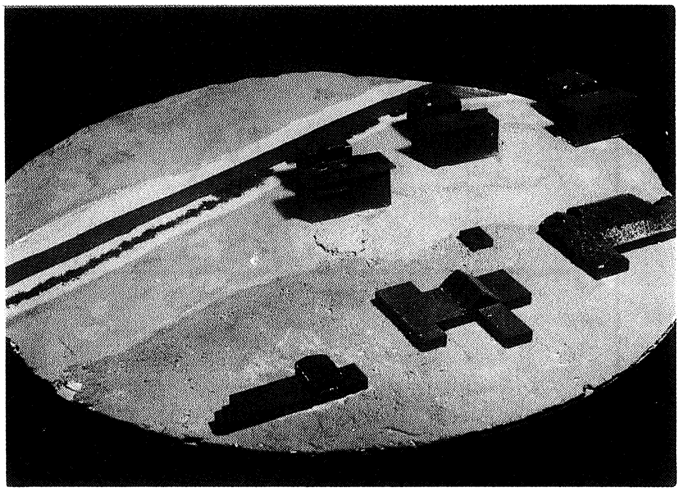
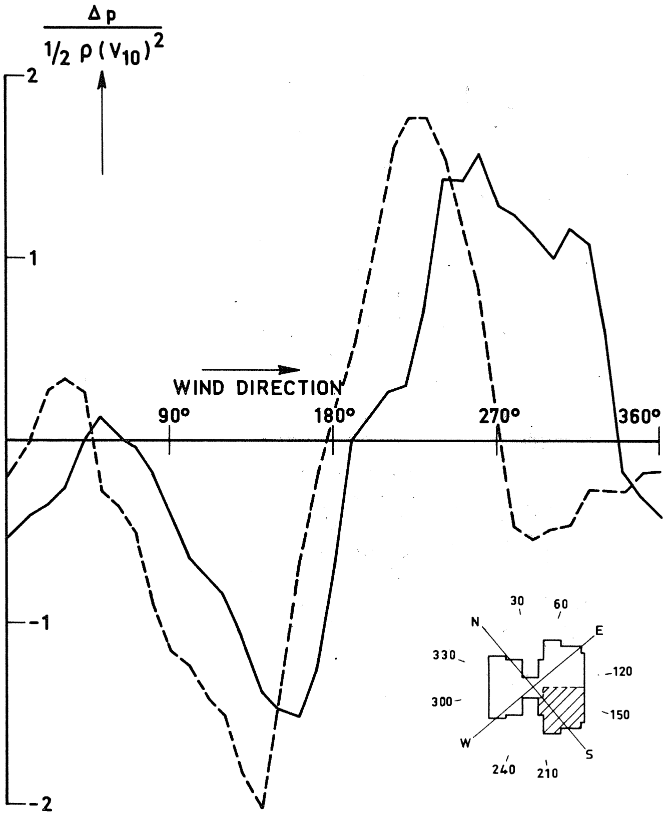
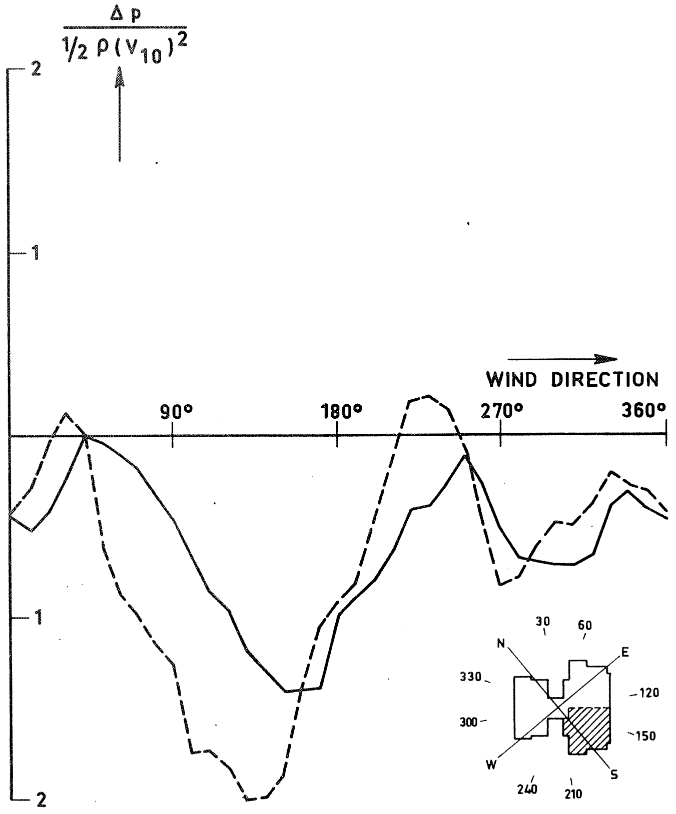


Fig. 8 Photograph of simulated buildings



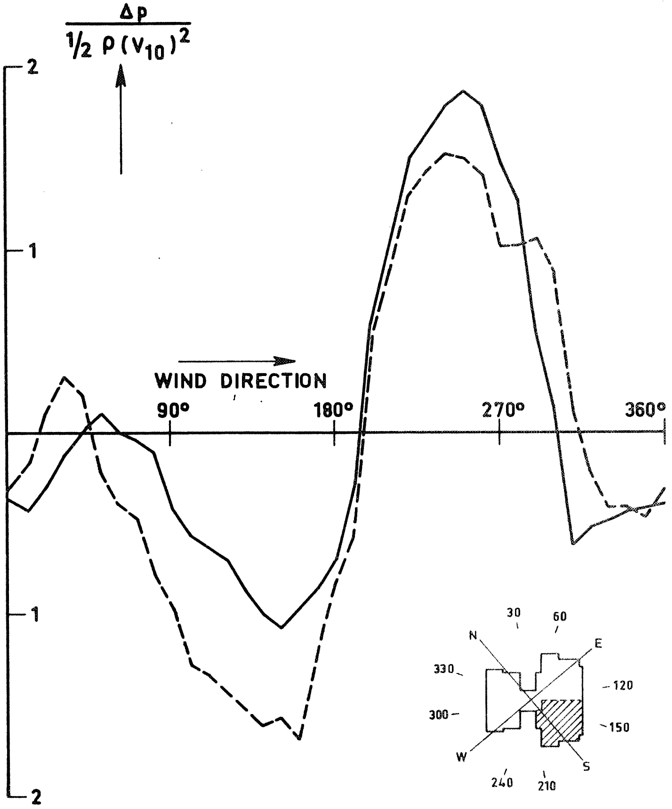
WIND TUNNEL MEASUREMENTS
SW-SE WALL

Fig. 9



WIND TUNNEL MEASUREMENTS
ROOF - SE WALL

Fig. 10



WIND TUNNEL MEASUREMENTS
NW - SE WALL

Fig. 11

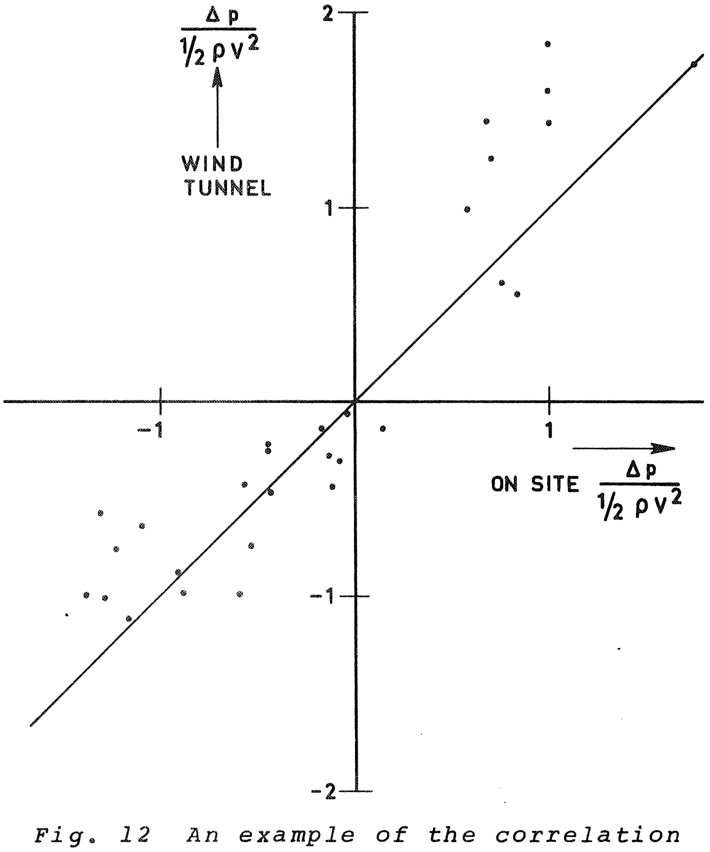
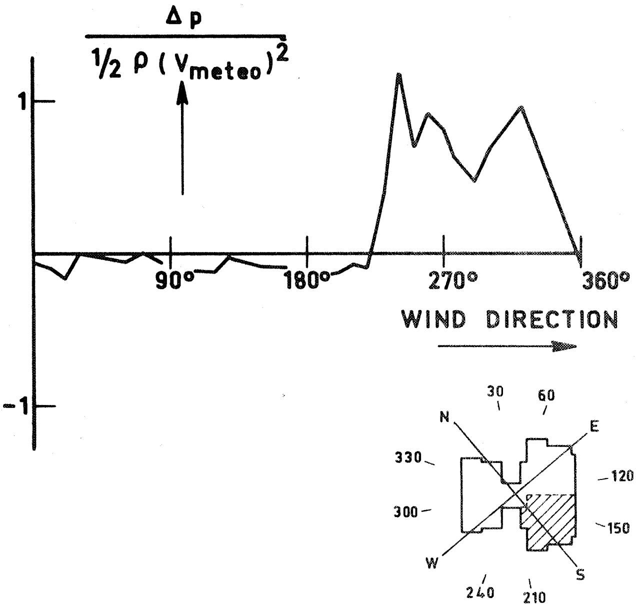


Fig. 12 An example of the correlation coefficient for comparison of wind tunnel and site measurements (see also Table 2)



PRESSURE DIFFERENCE
INSIDE - NW WALL

Fig. 13