AIR INFILTRATION REDUCTION IN EXISTING BUILDINGS

4th AIC Conference, September 26-28 1983, Elm, Switzerland

PAPER 7

AN OVERVIEW OF VENTILATION RESEARCH IN LARGE NON-RESIDENTIAL BUILDINGS

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SYNOPSIS

A short treatment of the concepts and aspects that play a role in ventilation is followed by a brief description of the investigation methods employed. A concise survey of the equipment and mathematical models used is given. The ventilation research carried out by the IMG-TNO is reviewed. Objects treated are factories, laboratories, hospitals, auction halls and similar buildings.
In the evaluation and conclusions it is suggested that:
* almost no research into local ventilation provisions has been carried out;
* the choice between natural and mechanical ventilation is a difficult one;
* there is a lack of knowledge regarding the influence of turbulence on ventialtion.

1. INTRODUCTION

Ventilation of buildings means the removal of stale air and the supply of fresh air. Stale air contains not only CO_2 due to human respiration and body odours, but also pollutants of many kinds released by processes carried out in buildings, that can in some cases be merely a nuisance but in certain circumstances can be posionous.
This publication, however, takes a wider view of ventilation. It is concerned with the area of knowledge that covers the transport of air through buildings, to which the control of air pressure differences and air flow devices is inherent.
In the last few years, partly as a result of the energy crisis, a great deal of knowledge concerning the ventilation of dwellings has been acquired. Relatively little is known regarding buildings other than dwellings. In most cases the research that has been carried out can be regarded only as "case studies". There is almost no question of systematic research covering the whole field.
On the basis of the investigations carried out by the IMG-TNO over the last 10 years, and an evaluation of these, an attempt is made to indicate the fields for future investigation.
The investigations described in the survey are confined to the aspects of air exchange, and the transport of air and the pollutants it contains. Investigations more concerned with comfort are only touched upon in the survey.

2. THE VENTILATION OF BUILDINGS

2.1 General

Ventilation of buildings is produced by differences in air pressure that cause air to be transported.
Such differences in air pressure can arise from natural "forces", such as wind and temperature differences, but also from mechanical "forces" such as fans.
Very often both types of forces are concerned. The correct balancing of the two is a matter than deserves particular attention.
Designers frequently opt for mechanical extraction in large buildings in order to meet the requirements for ventilation. Natural ventilation is scarcely considered. This is due to the lack of insight into the process of ventilation and the lack of means for calculating the ventilating effect as a function of wind speed, wind direction and temperature difference.
When mechanical extraction is used, fresh air is supplied via natural ventilating devices such as grilles, open windows or cracks and joints. The building is then subject to excess pressure with respect to the atmosphere or neighbouring buildings. In such cases the opening of an outer door or a connecting door can cause an undesirable flow of air.

Another aspect of building ventilation is the movement of air in a space due to ventilation. At certain points clean air will enter, while at other points polluted air will often be extracted. Air extraction has little influence on the movement of air within the space. The supply of air, however, can have an overwheling effect. This must be taken into account so far as the distribution of pollutants and/or heat is concerned. The extraction of pollutants or excess heat can then best be effected by removing them at source as far as that is possible.

In general, the ventilation of buildings depends on:
- the exterior conditions (wind and temperature);
- the building (geometry, design, situation, position of openings);
- the purpose of the building;
- the presence or absence of mechanical ventilation.

2.2 Pressure Differences

2.2.1 Wind

Due to the presence of atmospheric pressure differences movements of air take place (winds). The extent of such movements depends partly on the roughness of the earth's surface. When the wind strikes a building, a part of the kinetic energy will be converted into a pressure. A surface facing the wind (windward) will experience a higher pressure than the opposite (leeward) surface, and than an surface more or less horizontal to the wind (the roof). See figure 1.
This can be expressed as:

$$\Delta p = k.\tfrac{1}{2}\, v^2 \rho \qquad (1)$$

where

Δp =	pressure difference on an external wall	[Pa]
k =	a dimensionless pressure coefficient depending on the form of the building and the exposure	[ ]
ρ =	air density	[kg/m³]
v =	wind velocity	[m/s]

2.2.2 Stack Effect

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

$$\Delta p = (\rho_c - \rho_w).g.h$$

where

Δp =	pressure difference (stack effect)	[Pa]
ρ =	air density	[kg/m³]
c =	cold air	
w =	warm air	
g =	gravitational force	[N/kg]
h =	height between inlet and outlet openings	[m]

Figure 1 Natural ventilation by ....

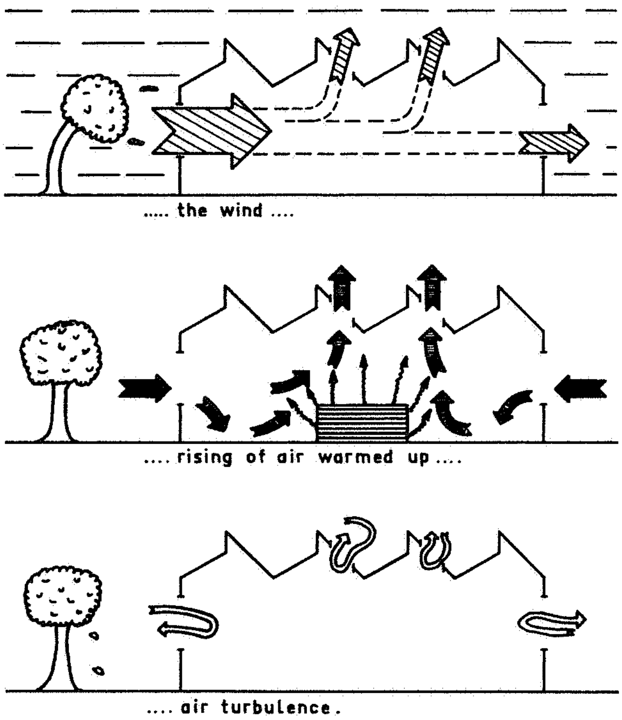
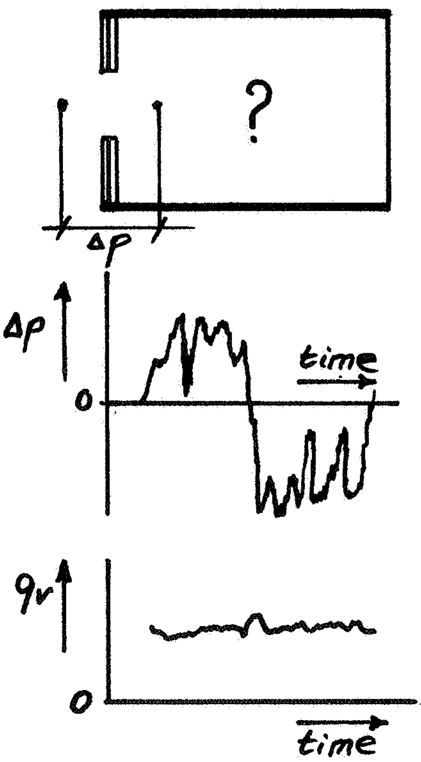


Figure 2. Turbulence



Building with one

ventilation opening

Pressure difference

sometimes positive
sometimes negative

mean pressure is zero

ventilation

For building ventilation the following factors are important in relation to pressure differences:

- the pressure on the exterior of a building as a function of wind velocity and direction;
- the pressure differences across all ventilation openings as a result of the pressures on the exterior and the distribution of the openings, both in the outer skin and in the interior walls;
- the effect of immediately adjacent buildings or vegetation on the pressure differences;
- the effect of the situation on the pressure differences (for example, building density, coast/inland, high/low);
- the effect of the form of the building;
- the effect on the ventilation of fluctuating pressures resulting from turbulence (figures 1 and 2).

2.3 Air Flow through Openings

In addition to air pressure differences, ventilation also requires openings.

Inevitable joints, cracks and gaps, but also special ventilation provisions such as ventilation windows, grilles or ducts are the cause of an air flow through the building. The relationship between the individual air flows through any opening and the pressure difference across the latter can be expressed as:

$$q_v = C(\Delta p)^{\frac{1}{2}} \qquad (3)$$

where

q_v = volume flow rate of air [m³/s]
C = air-flow coefficient, defined as the volume flow rate of air at a pressure difference of 1 Pa [m³/s at 1 Pa]

C = f(A)
A = superficial area [m²]
p = pressure difference across opening [Pa]
n = a coefficient between 1 and 2, depending on the character of the flow
n = 1 for pure laminar flow
n = 2 for pure turbulent flow

For the purposes of investigating ventilation, knolwedge of the location and the size of all openings in the building is therefore required.

3. INVESTIGATION METHODS

3.1 General

The organization of the investigation is determined by the nature of the problem, and by whether it is to be carried out in the

design phase (prediction) or on an existing building (usually troubleshooting).
In the case of a predictive investigation in the design phase, the ideal situation would be:

Determination of the pressure distribution in a wind tunnel, using a model of the building and simulation of the immediate surroundings.
The carrying out of calculations with the aid of a mathematical model.

The mathematical model, using as input the pressures determined in a wind tunnel, allows a parameter study to be made with which pressure differences, volume flows, air flow directions, ventilation volumes, air velocities and the concentrations of pollutants can be studied in relation to each other.

With investigations of existing buildings, measurements can also be made, depending on the nature of the problem. It is usually impossible in the case of fairly large buildings that are not intended as dwellings, to solve a problem solely by measurements. The results of measurements on existing buildings or installations are often dependent on weather conditions, productive capacity, etc. In such cases the situation is determined for normally occuring circumstances, usually confined to a restricted area.
The aim is then to simulate the same circumstances as accurately as possible with the aid of mathematical models. A parameter study can then be performed on the mathematical model.

In some cases, particularly where concentration and temperature distributions, stratification and control of air flow directions are concerned, tests on scale models may be necessary. In such cases account must be taken of the model rules and the associated characteristic numbers such as the Froude, Grashof and Archimedes Numbers.

3.2 Measuring Equipment

In addition to mathematical models, scale models and a wind tunnel, a large number of facilities and instruments are available for ventilation investigations.
Up to 1975 recordings were made on multi-channel recorders. Since then, and almost without exception, use has been made of a data acquisition system consisting of a controller, DV meter and scanner.
A survey of the measuring equipment in use is given in Table 1.

TABLE 1 Measuring Equipment in Use

Quantity to be measured	Instrument
Air velocity	- Velocity meter - Vane anemometer - Thermoelectric anemometer - Pressure plate*
Air pressure differences	- Betz micromanometer - Electronic pressure sensor
Volume flows	- Pitot tube - Orifice plate
Ventilation factor	- Katharometer - Infrared spectrometer
Concentration	- Various instruments, depending on the component to be measured

* This is a instrument specially developed for measuring flows through large openings, with which the value and the direction of the flow normal to the flow area can be determined [1].

The IMG-TNO wind tunnel is of the open-return type with a cross section of 1, 1 x 1, 1 m at the measuring section. The ground roughness of the distant surroundings are simulated by strips over a length of approximately 6 metres. The direct surroundings of the building under investigation are modelled to scale.

3.3 Mathematical Model

A space in the model is called a junction. In the static case the sum of the incoming air mass flows at a junction must be equal to the sum of the outgoing air mass flows. In general there is a given pressure for each junction at which this will occur. The computer program iteratively calculates for each junction the pressure at which the air flows are balanced. In practice the pressure in a space will fluctuate somewhat in the conditions used by the computer program. The instantaneous values of the actual air flows will therefore be slightly out of balance, but the average values will be the same as those given by the computer program.

Because of these fluctuations the actual ventilation is somewhat higher than that calculated on the basis of the time-averaged pressures. The program includes an approximation calculation that allows the effect of such turbulent air exchanges to be calculated.

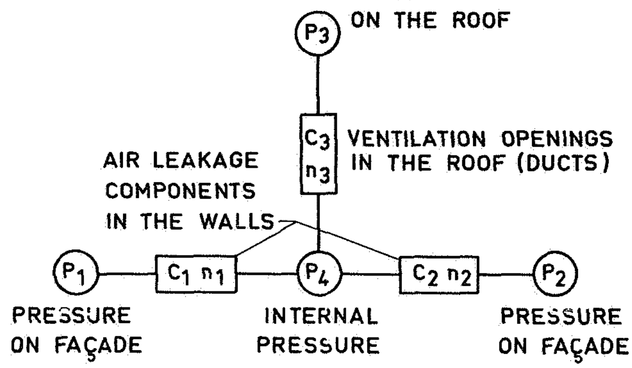
The program allows the use of fans to be simulated. The temperatures in the program are input values and do not change when the ventilation flow changes.

The program is intended primarily for calculating the ventilation of buildings. In these the air velocities in the spaces are so low that the pressures due to them can be neglected in comparison with the pressure differences across air leaks between spaces or across the facade [2,3].

The IMG calculation model for ventilation has been in use since 1977. Up till then use was made of an electrical analogue model specially developed for the purpose [4].

Figure 3

One-junction ventilation model



4. REVIEW OF INVESTIGATIONS UNDERTAKEN

This chapter provides a review of the most important investigations that have been carried out by IMG-TNO during the last 10 years.
The review includes investigations undertaken for third parties, for which results can not be published. In these cases an overall description of the problem and the approach is given, together with a fictional example of the results.

Before describing the investigation carried out for each type of building, a more general study will be discussed first.

4.1 Model Tests of Wind Pressure Distribution across some General Forms of Building

In this investigation [5, 6] the average wind pressures on the facades and roofs were measured with five types of building (see figure 4). The scale of the models was 1:200. The measurements were made with varying wind directions and three values of ground roughness. The influece of the immediate surroundings was also investigated. For this purpose a second building was placed at varying distances from the building under test. An approximation method for estimating pressures in situations different from those of the test is given. Some results are illustrated in figures 5, 6 and 7.

4.2 Factories

A total of five factory buildings were tested, having gross volumes of 40 000 m^3 to 108 000 m^3 [2, 7, 8].
The buildings concerned were a foundry, an ore-pelleting plant, an electrolytic plating plant, a fabric printing works and a chemical factory.

In almost all cases a significant part of the ventilation was provided by thermal "forces".
The nature of the problem varied only slightly from case to case. Pollutants generated by the production processes had to be removed. The distribution of pollutants had to be restricted. This meant studies not only of the mechanical extraction provisions but of the air flow patterns as well. The pollutants consisted of:

zinc oxide in the foundry;
fluorides and dust in the pelleting plant;
oil mist in the electrolytic plating plant;
white spirit and moisture in the printing works;
mercury vapour in the chemical factory.

In the pelleting plant and the plating plant measurements of the pollutants formed part of the investigation.
In almost all cases balancing of the possibilities for natural and mechanical ventilation was included in the investigation.
A very extensive scale model test was carried out for the electrolytic plating plant [9, 10].
No measurements of the effectiveness of the local extractors were made apart from determination of the extracted volume flows.
In all cases mathematical models were used to calculate the dimensions of the mechanical and natural ventilation systems.
The conclusions of the investigation can be summarized as follows:

- Observation of the air flows in four of the five cases allowed improvements to be indicated without having to measure the effectiveness of the local extraction equipment.

- The ventilation systems in use could in all cases be improved. In most cases this involved fitting sufficient, mutually matched and adjustable ventilation openings. These were usually too small by a factor of 5 to 10. In addition the distribution of the extraction and supply openings over the roofs and facades left something to be desired. The general tendency was to pay more attention to the roof openings than to adequate supply provisions, spread over several facades. This was in spite of the fact that mechanical extractors were already fitted.

Examples of the results of the investigation are given in figure 8 and tables 2 and 3.

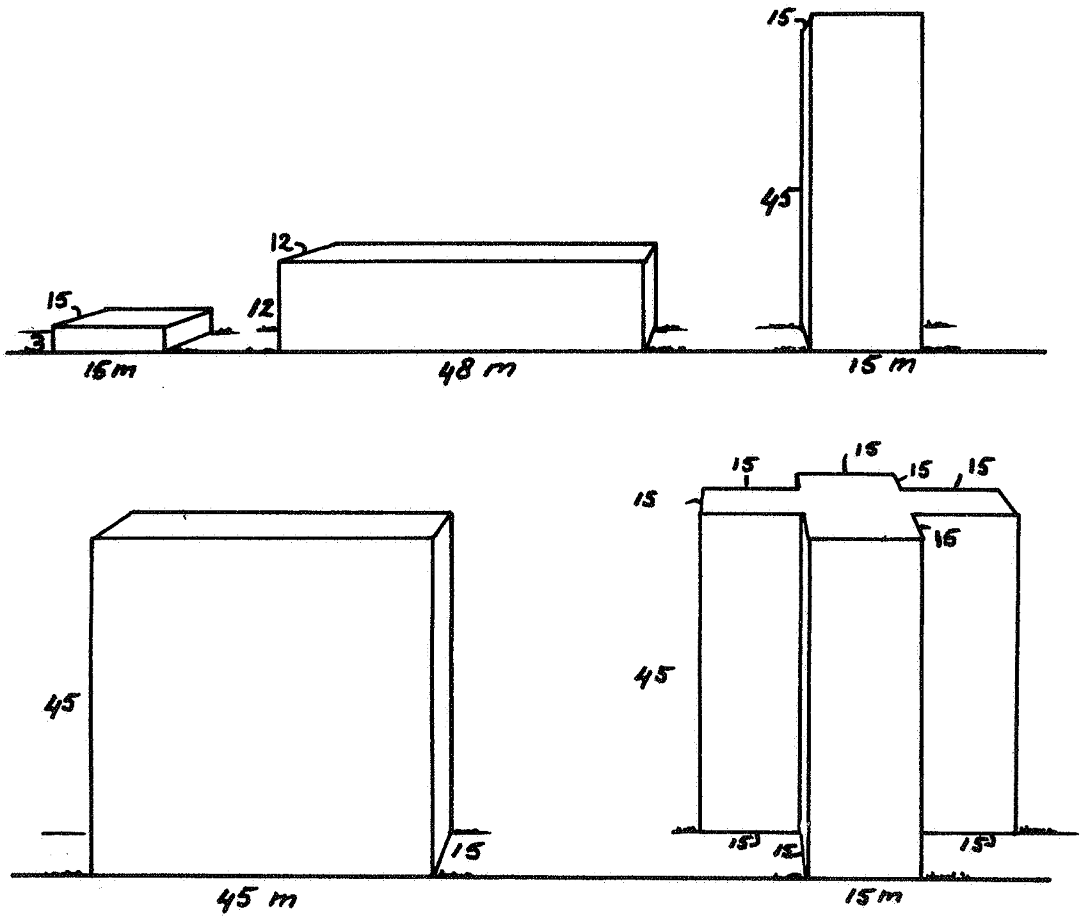
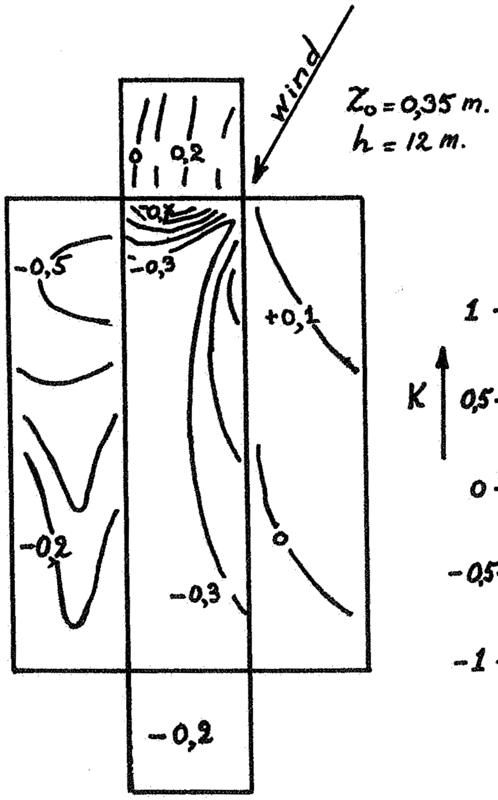


Figure 4 Building forms



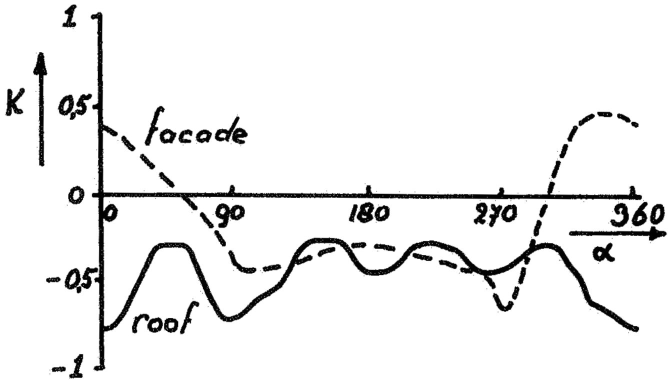


Figure 5 Pressure distribution

Figure 6 Direction dependent pressure differences

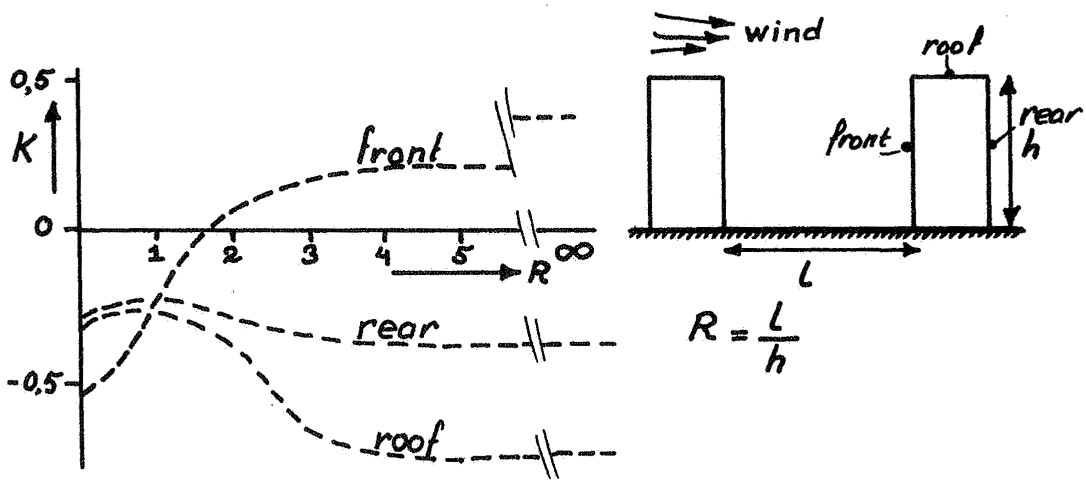


Figure 7 Influence of obstacles at various distances

TABLE 2

Mass flows based on	Q_1	Q_2	Q_3	Q_4	Air change rate (h^{-1})
		(kg/s)			
Velocity measurements	861	50	707	133	32
Pressure measurements	807	50	694	133	34
Calculation model	787	72	726	133	30

In a factory hall, with a capacity of about 87 000 m^3, a large number of measurements has been done to find the relation between the air-flow pattern, temperature distribution and spread of dust. [8]. In this factory hall the air velocity in every opening was measured during periods of about four hours. In total some hundreds of air velocities have been measured. From these velocities and the net area of the openings, the mass flow through the factory hall could be computed. Pressure differences across openings have been measured with the aid of five differential low pressure transducers. Also, the mass flow has been computed from these data. Finally the different mass flows and the resulting air change rate with the calculation method described have been predicted.

TABLE 3

Air change rate h^{-1}

Direction α				90°			60°			30°		
Ratios of ventilation openings				Wind velocity								
Windward	Leeward	Roof		2	6	10	2	6	10	2	6	10
1	1	1		33	40	64	33	39	61	33	34	52
½	1	1		30	32	34	30	32	32	30	31	30
1	½	1		31	40	60	31	38	58	30	34	50
½	1	½		19	20	33	19	20	32	19	19	27

$\Delta T = 7{,}5$ K
Air change rate by the process = 4 h^{-1}
(velocity in m/s)

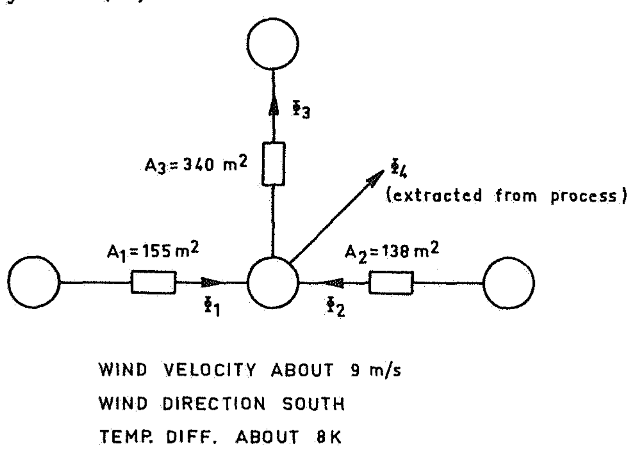


Figure 8
Ventilation model of the factory hall.

In figure 8 the model of the factory hall and the conditions in the hall are shown. From table 2 it can be seen that the measured and the calculated values agree rather well.

Table 3 shows values calculated with the method described above, especially for the engineering department of the factory. The air change rate (h^{-1}) is given as a function of:

- wind velocity
- wind direction
- position of the ventilation openings.

Figure 9, for the foundry, shows the measured pressure differences compared with those obtained from the calculation model, with a net mechanically extracted flow of 80 kg/s. The foundry has a gross volume of approximately 40 000 m³. The pressure differences were measured:

- between the interior and the South facade;
- between the interior and the North facade;
- between the interior and the roof;
- between the foundry and the neighbouring building.

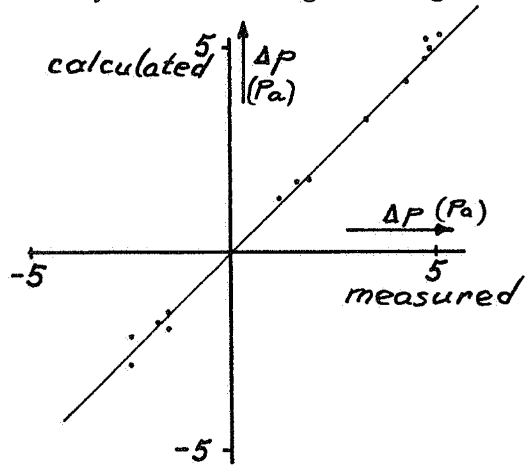


Figure 9 Comparison of calculated and measured pressure differences

The agreement between the calculated and the measured pressure differences can be considered as good. However, it should be remembered that a variation of 0,5 Pa in a pressure difference across a facade results in a mass flow variation of the order of 30 kg/s. With a total mass flow of approximately 100 kg/s in average circumstances, this represents a variation of 30%.

4.3 Laboratories

Nine investigations have been carried out, of which involved the ventilation characteristics of fume chambers [11]. In two cases the air management in the laboratory was investigated in combination with the operation of the fume chamber [12]. In the other two laboratories the problem was control of the air flows.

4.3.1 Fume Chambers

Most of the fume chambers investigated in laboratories were inadequate so far as the air velocity in the window opening was concerned, using a criterior of 0,25 m/s. The distribution of air velocities over the window opening also left something to be desired. In particular, the air velocity near the sharp-cornered edges was often too low.
With a number of fume chambers the volume of air extracted was not constant, depending on the size of the opening. This naturally had its effects on the air supply to the laboratory and, when the air supply system was inadequately compensated, influenced the pressure and the directions of air flow.

In some cases tests were made with tracer gases to determine the velocity in the opening at which egression of the gas took place. The tracer gases used were helium, carbon dioxide and Freon. It appeared that if an air foil is fitted (see figure 10) no egression of light or heavy gases can be expected so long as the velocity criterion of 0,25 m/s is satisfied.

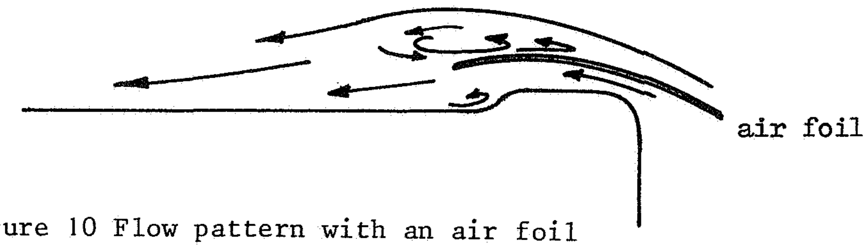


Figure 10 Flow pattern with an air foil

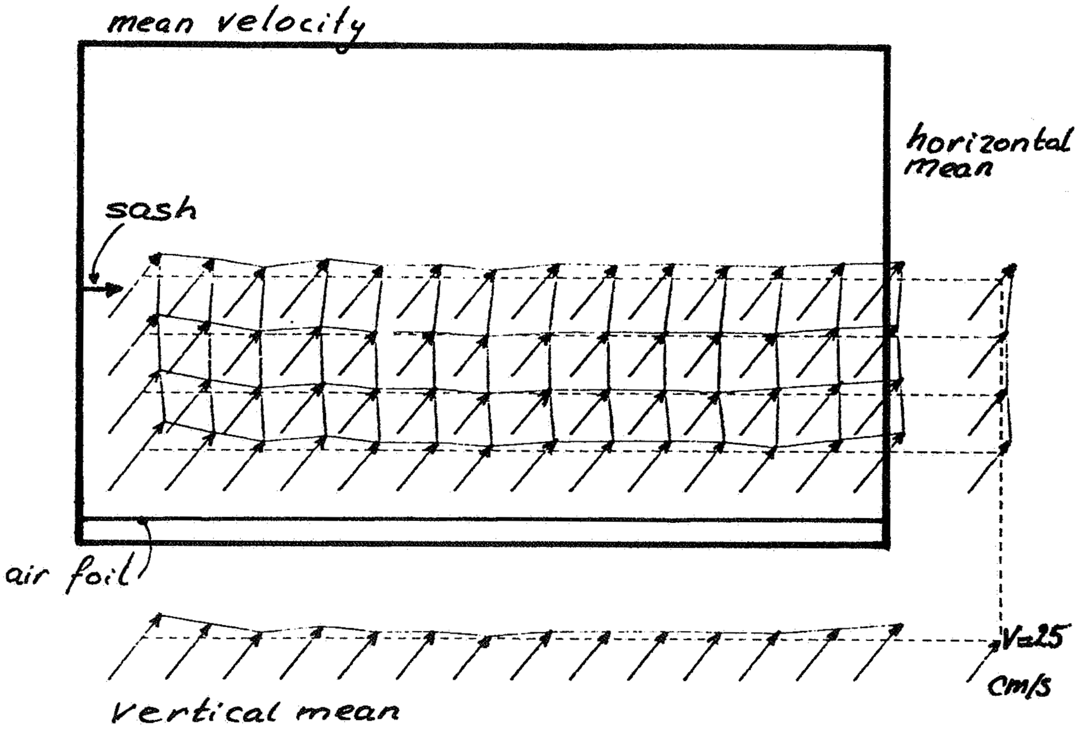
The effects of disturbances such as arm movements and passers by were also investigated.
A person sitting in front of the fume chamber and moving his arm through the plane of the window is exposed at nose height to concentrations of approximately 1.10^{-6} (1 ppm) when the concentration in the fume chamber was 1. Walking past the fume chamber can cause short-term increases in concentration to approximately 1.10^{-2} (about 1%).

It is not possible to prevent the egression of gas from the fume chamber by increasing the velocity through the window opening to about 0,4 m/s.

An examples of the air velocity distribution across the window opening, and the standard deviation of the velocities, is shown in figure 11.

4.3.2 The Prevention of Infiltration

The question in one still to be constructed laboratory was the prevention of infiltration, even under extreme weather conditions. Laboratory animals must be born in sterile conditions (without



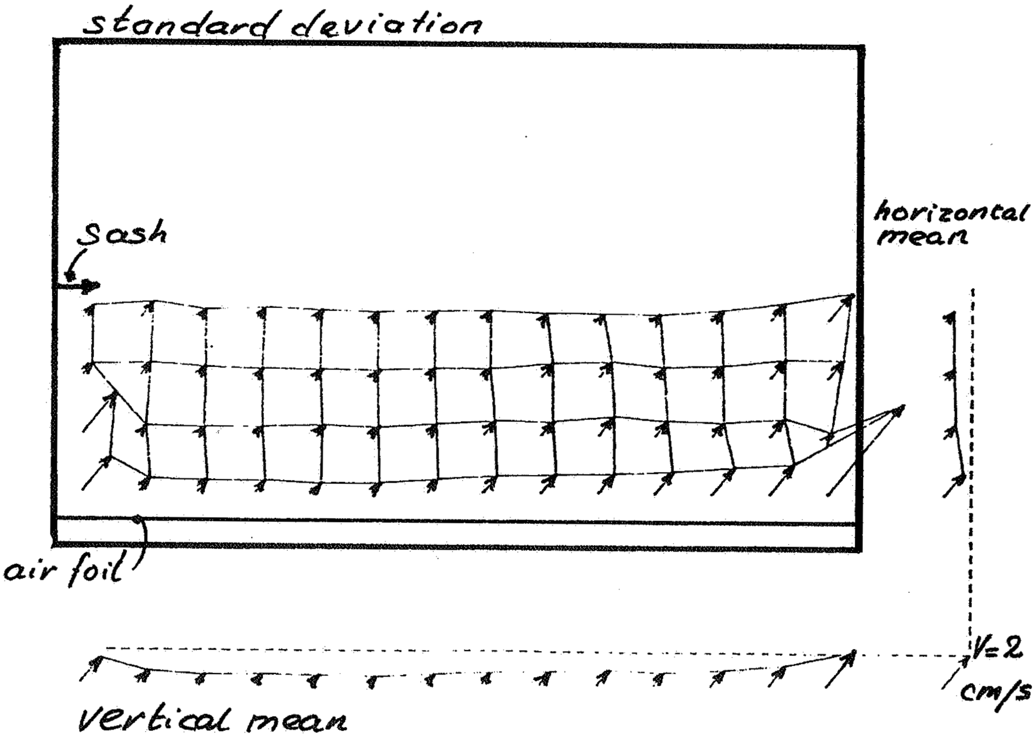


Figure 11 Air velocity distribution

contact with germs from outside) The criterion set was that infiltration must be prevented for 98% of the time. To reduce the influence of the wind on the building it was proposed to surround it with an earth wall. The effect of such a wall on the pressure distribution was tested in the wind tunnel. The flow distribution and the pressure distribution over the building was then examined with the aid of electrical analogue simulation. As a result of this investigation criteria were suggested to which the air handling system, including the filters, and the airtightness of the facades would have to comply. In the meanwhile the building has been completed and operates to the satisfaction of its users.

4.3.3 The Prevention of Exfiltration

A future laboratory was to be used for animal tests with virusses that were dangerous to human beings. The transport of unfiltered air to the exterior (exfiltration), and of germs from one room to another had to be prevented.
In this case account was taken of the hourly-average wind velocity of 24 m/s that is exceeded on the Dutch coast only 0,1% of the time.
The results of the investigation can be summarized as follows:
- the division of the building required modification at some points, access and location of clean and contaminated areas.
- Requirements regarding airtightness could be formulated, which had to be met not only the facades but also by the interior doors and walls.
- Requirements were laid down for the air handling installation, including the filters and regulation system.

4.4 Hospitals

In hospitals, as in laboratories, the control of pressure differences and air-flow directions plays an important role. The avoidance of cross-infection has been the subject of a large number of studies [13, 14, 15, 16]. In addition, extensive investigations have been made into the ventilation and air-flow aspects of operating rooms and surgical departments [17, 18, 19, 20, 21]. Air treatment installations, becuase of the large amount of space they occupy, can have a large effect on the height of the building and on the building costs. This has led to a study of the air duct system [22]. As a result of the study a large number of practical rules for achieving minimal total running costs has been obtained.

To conclude this paragraph on hospitals a further example is given, concerning a hospital for which an investigation was carried out in the design stage, and measurements made on the completed building [23].

In the design stage, the pressure distribution on the facade of the building was determined in the wind tunnel, and that in the interior by means of electrical analogue simulation. These pressure differences were later measured in practice (figures 12, 13 and 14).

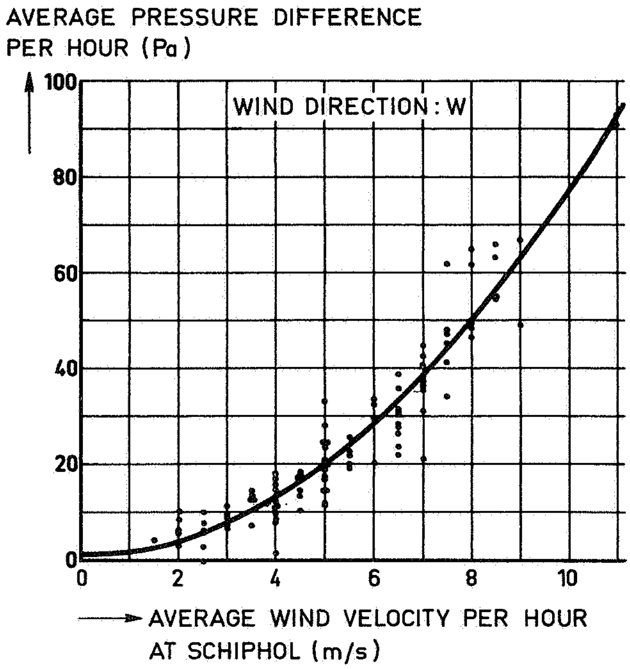


Figure 12a Relationship between the pressure difference measured and the wind velocity at Schiphol with west wind.

4.5 Parking Garages, Tunnels and Shopping Centres

Investigations have been made on three parking garages [24], three tunnels and three shopping centres.
The work consisted mainly of measurement of the pressure differences in the wind tunnel, and a parameter study with the aid of the IMG-TNO mathematical model for ventilation, or a specially-developed model in the case of tunnels.
The problem was concerned with the dimensioning of the ventilating facilites, and usually also with fume dispersal in regard to safe emergemcy exits. Stratification of fumes and the moment at which stratified fumes would be converted into turbulent mixtures played an important part in this case.

4.6 Auction Halls

A study of the possibilities for natural ventilation in auction halls in Bleiswijk has been made. For this purpose, calculations were carried out with a computer program specially developed for ventilation problems. As input data, results of wind tunnel tests were used [25].
For the auction, the ventilation must provide for:
a) discharge of solar heat as much as possible in the summer time because of the perishability of the products delivered (veget-

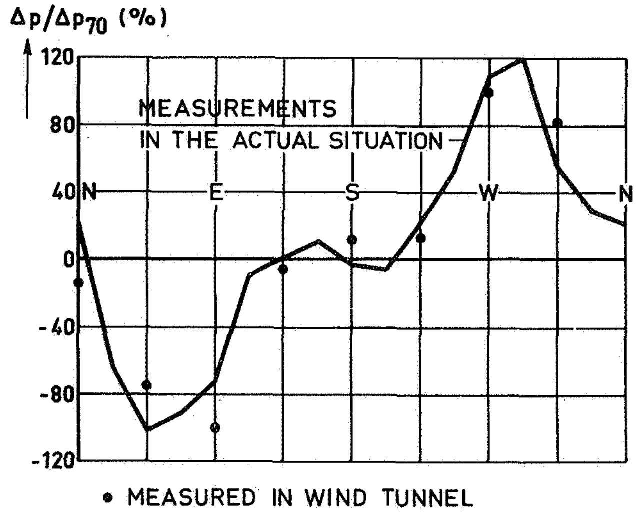
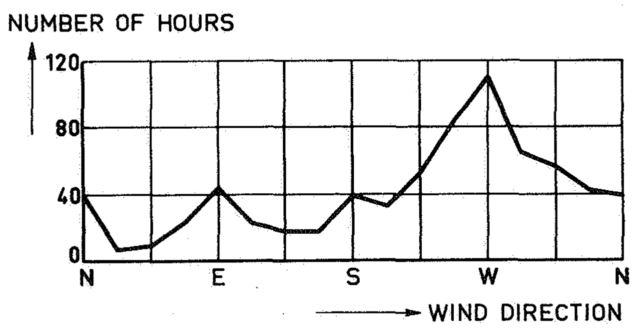


Fig. 12b *Pressure difference measured as a function of wind direction.*

Fig. 13 *Number of hours per wind direction*



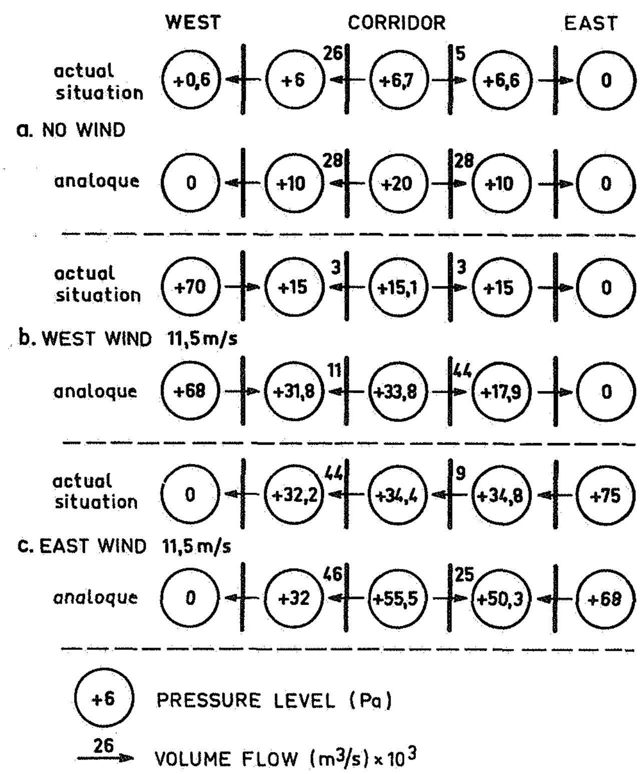


Figure 14
Measuring results on the 9h floor in north wing with closed windows.

ables) when exposed to higher temperatures (figure 15).
b) effective rarefaction of exhaust gases. These are produced by vehicles used for the supply, removal and internal transport of the vegetables (see figure 16).
Both demands are particularly pertinent for the ground level where persons will be exposed to the prevailing exhaust gases and the vegetables stored there to the local temperatures.

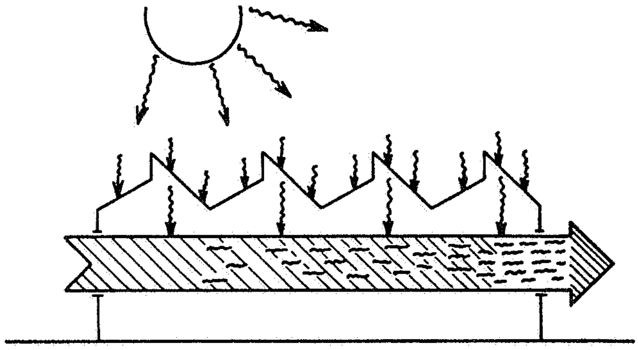


Fig. 15 Ventilation for removal of solar heat.

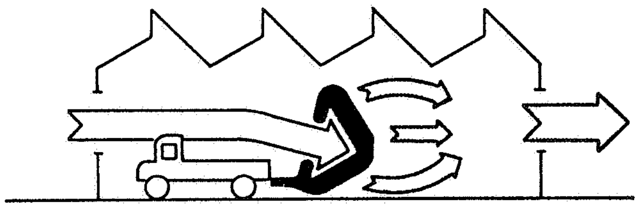


Fig. 16 Ventilation for dilution of exhaust gases.

The parts of the halls important for the investigation all have a length of 270 m, a width of 82 m and a mean height of ridge of 12,1 m.
The volume of such a part of a hall is about 200 000 m^3.

Some examples of results from this study are given in figures 17, 18 and 19.

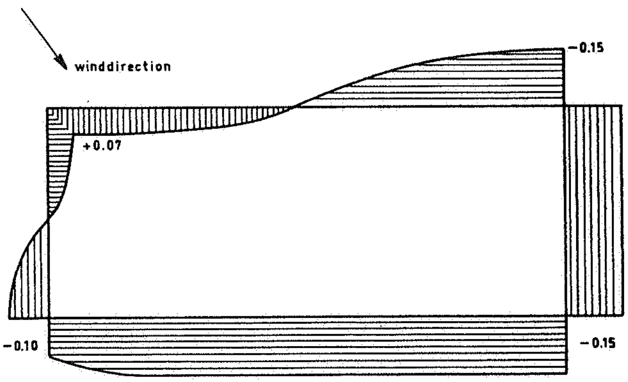


Fig.17 Wind pressure distribution on the fronts of hall 3 at easterly wind.

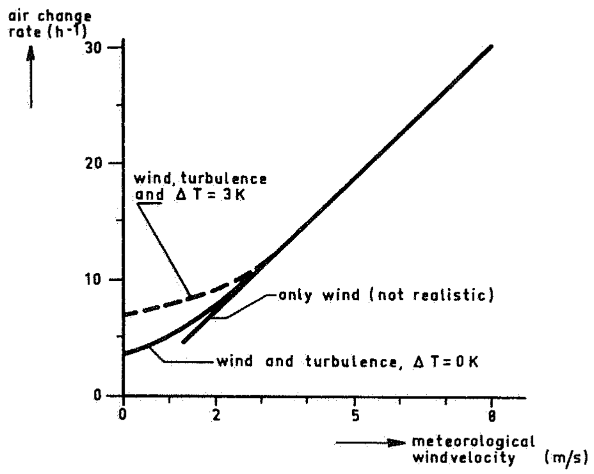


Fig.18 Air change rate curves depending on wind, turbulence and temperature differences.

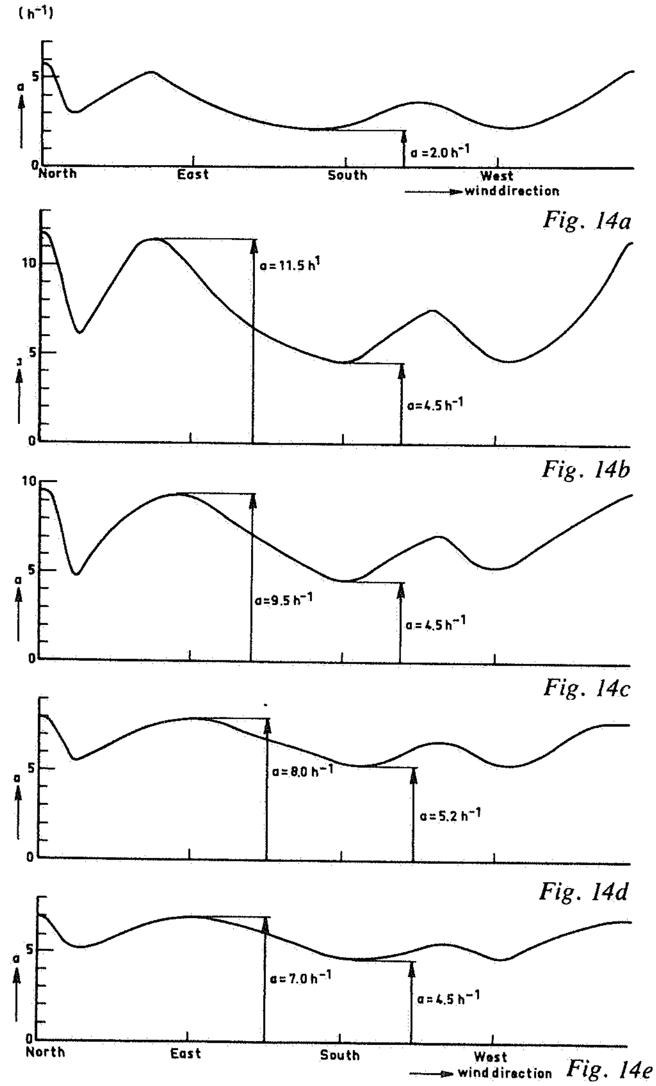


Fig. 19 Optimization of the size of the ventilating devices by means of the calculated course of the air change rate with the wind direction

By changing the ventilation design systematically and by determining the related changes in the degree of ventilation, an optimum ventilating system can be developed.
It appears that a natural ventilating system can be realized for the three vegetable auction halls by placing ventilating devices exclusively in the roof. The ventilation is then chiefly provided by the differences in wind pressure caused by the shape of the roof.

5. EVALUATION AND CONCLUSIONS

Study of the overview presented reveals that a relatively large number of studies have been made with regard to hospitals.
In the case of factories and other large buildings, investigations concerned with local provisions are relatively few. Nonetheless this certainly appears to be a field for deeper studies.
The reduction of pollutant concentrations in buildings involves the provision of facilities at the source of pollution [26]. Any other measures are generally less effective.
Local provisions include:
- enclosure of the source by means of covers, lids, etc;
- mechanical ventilation in or around the source;
- shielding of the source with a small air curtain;
- fitting an extractor hood around the source;
- combinations of the above.

Local provisions can have a negative effect on the ease of operating the process involved, but because of their positive effect on air pollution within the building their installation will in many cases prove to be a sound investment.
Since local provisions can not be used in every circumstance, the concentration of the residual pollution must be kep low by means of total ventilation of the building. It is usually the case that a large number of air changes (the ventilation factor) will be necessary.

Factories and halls are very often large in volume, resulting in large volume flows. Fitting large numbers of natural-flow inlets and outlets, distributed over the facade and roof, with regulation of the opening by simple manual means or by electric motors, offers the possiblity of large variations in ventilating flow due to thermal draught or wind pressure.

At this point it is relevant to quote from "Fundamentals of Industrial Ventilation" [27], in which Baturin had the following to say over the balance between natural and mechanical ventilation.

"Temperature differences and wind speed can cause the transfer of enormous quantities of air. For instance, measurements show that the natural air change in an open-hearth plant or a rolling mill amounts to about 20 million kg/hr. In forges, ironworks and other hot shops the air transfer may also be millions of kilograms per hour.
A very large consumption of energy would be required to move such quantities by mechanical means. The great economic importance of

natural ventilation is that it can bring about these air changes without expenditure of mechanical energy.
The time has long passed when it was necessary to demonstrate the benefits of natural ventilation and justify its application. The proofs were simple and very convincing. They were based on comparisons of mechanical ventilation and natural ventilation. In hot shops where all the emphasis was laid on mechanical ventilation, and natural air change, being regarded as unimportant, was not taken into account at all, it was found in all the tests that the volume of natural air change many times exceeded the volume of mechanical ventilation. This revealed the negligible role of general mechanical ventilation despite its heavy installation and running costs. Mechanical ventilation in thiese cases was best used as a corrective to natural ventilation, in the form of air curtains and local air supply or extraction.
In the hot seasons of the year natural ventilation can be used in almost every branch of industry, except the comparatively few industrial undertakings which require pretreatment of the air for technological reasons."

Turbulent influences have not yet been fully investigated. Knowledge of the effect of turbulence on ventilation is still lacking. This is particularly the case with industrial buildings with large openings for the purpose of natural ventilation. Air enters and leaves via these openings simultaneously, and with constant changes. Mathematical models are inadequate, even if they do take turbulent effects into account. Moreover, there is still no verification of their validity.

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