Natural ventilation of large multi-span greenhouses

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Foar heit en mem

STELLINGEN

1. De invloed van het raamtype op de door de wind aangedreven ventilatie van grote tuinbouwkassen kan niet verklaard worden door de stromingsweerstanden van de betreffende ramen alleen.

   (dit proefschrift)

2. Voor Venlo-kassen kan de gecombineerde lij- en loefzijde ventilatie, voor relatief kleine raamopeningen aan de loefzijde, betrouwbaar gekwantificeerd worden door de sommatie van de afzonderlijke lij- en loefzijde ventilatie.

   (dit proefschrift)

3. De door de wind aangedreven ventilatie van vrijstaande Venlo-kassen, per eenheid van raamoppervlak, kan worden beschreven als de som van de desbetreffende ventilatie door een oneindig kasdek en een bijdrage veroorzaakt door de aanwezigheid van de gevels (het geveleffect).

   (dit proefschrift)

4. Het geveleffect neemt toe met toenemend kasoppervlak.

   (dit proefschrift)

5. Bij de bepaling van de ventilatie in kleine, vrijstaande gebouw wordt veelal alleen uitgegaan van een statische drukverdeling om het gebouw. Het verdient echter aanbeveling ook de ventilatie tengevolge van de drukfluctuaties in de beschouwing te betrekken.

6. Het veronachtzamen van de drukafhankelijkheid van de microfoonkarakteristiek leidt tot een verkeerde interpretatie van fotoakoestisch gemeten gasconcentraties.

   Michael J. Kavaya, Jack S. Margolis and Michael S. Shumate, 1979. Applied Optics, vol 18, No. 15, 2602-2606.

7. Het is onjuist de berekening van oppervlakte-ruwheidsparameters louter op geometrische factoren te baseren.

   Adrie F. G. Jacobs and John H. van Boxel, 1988. Boundary-Layer Meteorology, 42, 265-279.

8. Het gebruik van het gemodificeerde Jaegermodel voor de uitwerking van warmtegeleidingsmetingen in bevriezende grond is principieel onjuist indien dit model niet wordt gemodificeerd.

   W.K.P. van Loon, I.A. van Haneghem and H.P.A. Boshoven. Proceedings of the 5th International Symposium on Ground Freezing, Nottingham, 26-28 july 1988.

9. De omslagfiguur van het boek "Transport Phenomena" van Beek en Muttzall geeft voet aan een ernstige misvatting.

W.J. Beek & K.M.K. Muttzall, 1977. Transport Phenomena.

10. Teneinde de onderzoeksresultaten op het gebied van luchtverontreiniging goed te kunnen vergelijken is op zijn minst standaardisatie van de bemonsterings- en ijkprocedure een absolute noodzaak.

11. De naam en het werkterrein van het oude ministerie van Onderwijs, Kunsten en Wetenschappen gaven terecht gestalte aan de artistieke beleving binnen de wetenschap.

12. Het verdient aanbeveling om in de onmiddellijke nabijheid van sierfonteinen openbare toiletten te plaatsen.

13. De introductie van 'high definition television' (HDTV) brengt ons vooral een scherper beeld van de vervlakking.

Stellingen behorende bij het proefschrift "Natural ventilation of large multi-span greenhouses" door Taeke de Jong.

Wageningen, 26 september 1990.

ABSTRACT

De Jong, T. (1990), Natural ventilation of large multi-span greenhouses. Ph.D. Thesis Agricultural University Wageningen, The Netherlands. 116 pp.; 46 eqs.; 44 fig.; 4 tables; 54 refs.; English and Dutch summaries.

In this thesis the ventilation of large multi-span greenhouses caused by wind and temperature effects is studied. Quantification of the ventilation is important to improve the control of the greenhouse climate.

Knowledge of the flow characteristics of the one-side-mounted windows of the greenhouses is essential to understand the ventilation process. An approach is presented which a priori describes the flow characteristics of the windows. This description is complemented with in situ measurements of the flow characteristics which definitely confirmed the given approach.

The air exchange caused by wind effects and the air exchange caused by temperature effects were considered separately.
As a starting point for the description of the greenhouse ventilation due to wind effects, the ventilation through a 'quasi-infinite' greenhouse cover was considered. The 'quasi-infinite' cover is defined as a greenhouse cover where the wind field near the surface is not influenced by any boundary effect. A description of the wind-driven ventilation through these greenhouse covers is presented and validated by full scale measurements. The leeside ventilation, the windward side ventilation and the combined leeside and windward side ventilation were studied. The effects of wind direction, wind speed, number of windows, window dimensions and opening angle were investigated. Parametrization of the theoretical model of the ventilation led to a reliable quantitative description of the air exchange of the 'quasi-infinite' greenhouses.
Results of ventilation measurements performed in differently sized free-standing greenhouses indicate that the ventilation characteristic of the 'quasi-infinite' greenhouse can well serve as a reference with respect to the ventilation of real (finite) greenhouses.

Though in practice the wind effects amply dominate the temperature effects, the effect of the thermal buoyancy is of fundamental interest. An approach was presented to describe the natural convection through the one-side-mounted windows. Ventilation experiments lend support to the given approach.
Next an expression for the combined effect of temperature and wind on the ventilation was suggested. Full scale measurements showed that this expression provides a good representation for practical purposes.

free descriptors: greenhouses, natural ventilation, greenhouse climate, one-side-mounted windows, flow characteristics, Venlo type greenhouses, tracer gas techniques

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EEN WOORD VOORAF

Het onderzoek waarvan de belangrijkste resultaten zijn neergelegd in dit proefschrift kwam tot stand door nauwe samenwerking van drie onderzoeksinstellingen, te weten: de toenmalige vakgroep Natuur- en Weerkunde (sectie Natuurkunde, thans deel uitmakende van de vakgroep Agrotechniek en -fysica) van de Landbouwuniversiteit Wageningen, het Proefstation voor Tuinbouw onder Glas (PTG) in Naaldwijk en het Instituut voor Mechanisatie, Arbeid en Gebouwen (IMAG) in Wageningen. Mede door deze constructie is een relatief groot aantal mensen betrokken geweest bij dit onderzoek. Deze plaats in het proefschrift biedt mij een goede gelegenheid om hen te bedanken voor hun bijdragen.

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1 INTRODUCTION

Protected cultivation, i.e. the cultivation of crops in transparant shelters or glasshouses, is probably one of the most striking examples of men's interference with the physical environment of a crop, in order to ensure or step up production. Due to practical experience and, more recently, the introduction of new materials and computer technology, the initially more or less simple modification of the environmental conditions of the plant could evolve in the course of time into the present climate control systems for modern greenhouses used for commercial agricultural production.

In particular, the introduction of the computer in greenhouse climate control facilitated climate management. Control functions can now be programmed and easily altered in accordance with the prevailing views or wishes. Modifications of the control functions are usually directed towards an increase of the final yield. The optimal climate control would eventually lead to the economical optimization of the greenhouse production system. To gain insight into this complex production system and its related optimality problem, targeted research was performed on the economical, biological and physical processes involved (among others: Udink ten Cate [1], Bot [2], Takakura et al. [3], Stanghellini [4], Challa et al. [5]). Nowadays, computers for climate control are mostly used with regard to the control of the air temperature and the avoidance of extreme situations in the greenhouse. As soon as insight into crop behaviour increases and control has to be imposed over more than one output variable (like humidity and carbon dioxide concentration), the dynamical behaviour of the greenhouse has to be known to attain optimal control.

An important process in the greenhouse is the air exchange between the inside of the greenhouse and the environment. It directly affects the transport of sensible heat, water vapour and other gases to or from the inside air. The needs for ventilation during greenhouse operation are obvious. These are, to control the temperature, to lower an excessive level of humidity caused by transpiration of moisture from the plant

foliage and to replenish or, since the importance of CO_2 enrichment is recognized (Schapendonk and Gaastra [6]), to control the concentration of CO_2 in the greenhouse. Therefore, more insight into this exchange mechanism is crucial to optimize the crop growth and to reduce the energy consumption during the cultivation of the crop.
The present research concentrates on the mechanisms behind ventilation in general and the ventilation of the Venlo type greenhouse in particular. It is intended to contribute basic elements to a quantitative description of the ventilation of Venlo type greenhouses, which would truly be an object of value with regard to horticultural climate control in The Netherlands, since this type of greenhouse covers about 80 percent of the total glasshouse area of about 9000 ha in this country. In addition to this, a better understanding of the mechanisms behind the ventilation process can be used to improve the greenhouse design. Moreover, the present work, though directed towards ventilation of Venlo type greenhouses, certainly also contains significant information with respect to ventilation of other types of greenhouses or even very different buildings, such as schools, hospitals, offices etc.

1.1 Previous greenhouse ventilation research

A great deal of research has been performed into all areas of ventilation phenomena. The following summary concerns itself with ventilation research related to greenhouses. The importance of the ventilation in greenhouses has been recognized for many years and can be considered as one of the most important climate control actions available for the grower. However, the quantification of the air exchange was a rather difficult matter for a long time.
In the middle of the fifties, a start was made to quantify the ventilation in greenhouses. Businger [7] investigated the air circulation inside a small glasshouse and estimated the corresponding magnitude of ventilation for different ways of ventilating by means of a simple heat balance over the glasshouse. Aiming for an equable distribution of fresh air, such that the crop is not directly contacted by cold draughts from the inflow of

fresh air, ventilation strategies, i.e. certain combinations of opened windows, were recommended. A more direct way to determine the ventilation air flux in greenhouses was introduced by Morris and Neale [8]. They published some data of measured ventilation rates of two relatively small greenhouses with both side and roof windows. The measurments were obtained by a tracer gas method. Their experimental data, however, were restricted and no relationship between the measured ventilation rates and relevant weather conditions was given.

The same tracer technique was also applied by Whittle and Lawrence [9], when they measured the ventilation in small greenhouses equipped with side and roof windows. A formula was established for leakage ventilation, presuming a linear relation between the ventilation and the outside windspeed. The air temperature difference between the greenhouse air and the outside air was not found to be significant in case of leakage ventilation. For ventilated greenhouses, no relationship between the ventilation and other relevant factors was obtained.

Much later research was aimed at the determination of the leakage and its relationship with greenhouse construction or environmental factors like wind speed, wind direction and difference in temperature between the greenhouse air and outside air. Roer [10] compared the tightness of different types of glasshouse constructions by measuring the overpressure when a (known) quantity of air is blown into the glasshouse. Gudehus [11] investigated the air exchange through leaks in a similar way. This method was proposed to serve as a standard technique to determine leakage of different greenhouses. Heissner [12], using a radioactive tracer gas, found a linear relationship between the measured leakage and the outside wind velocity for different closed greenhouses.

Okada and Takakura [13] derived, through theoretical considerations, an equation for the air exchange in greenhouses. They expressed the rate of air infiltration as a sum of two terms, proportional to the outside wind speed and the square root of the temperature difference respectively. Experimental data of measured leakage ventilation were fitted to this equation. To be able to compare different greenhouses, they suggested expressing the leakage in m^3 per unit wall area. The effect of wind direction was not considered. Van Berkel [14] investigated the distribution and exchange rate of CO_2 from gas-fired heating boilers. He calculated the air exchange rates from measurements of CO_2 concentration performed during the night period. For the glasshouse with closed ventilators, a relation was found between the exchange rate and the wind speed (in Beaufort figures) raised to the square. By opening the ventilators, an increase of the air exchange was measured but no quantification was given.

The first (theoretical) model approach for greenhouse ventilation was presented by Kozai and Sase [15]. They developed a computer program for estimating the natural ventilation in multi-span greenhouses, starting from basic relationships between the flow rate and existing pressures due to temperature or wind effects for one opening. The coefficients in these relationships were based on wind tunnel experiments. The ventilation was calculated for greenhouses with a different number of spans, varying from one to four, all equipped with both side and roof ventilators. Afterwards, this model was extended by Kozai, Sase and Nara [16] who incorporated a heat balance and some coefficients based on greenhouse model studies in a wind tunnel. The ventilation model was used to simulate ventilation rates and the greenhouse air temperature. Though their work was not based on full scale measurements, insight was gained on the relationship between the air exchange and some relevant factors like window opening, wind speed and temperature difference.

Bot [2] was the first to introduce a general approach to describe the ventilation through the windows of large Venlo type greenhouses. Ventilation characteristics of the greenhouse were related to window type, opening angle and environmental factors like wind speed, wind direction and temperature difference. However, many empirical relations were based on model studies and full scale measurements were only carried out in a small compartment by means of a static tracer technique. Ventilation in the same compartments were also measured by Nederhoff et al. [17] by means of a dynamic tracer technique for small window openings. Their experimental results were in agreement with the findings of Bot. Rüther [18] determined natural ventilation rates of closed greenhouses with CO_2 and N_2O as tracer gases. Results of measurements before and after tightening one greenhouse were compared. Generally, a linear dependency on wind velocity and temperature difference was found. No effect of wind direction on the leakage seemed to be present. Baytorun [19] extensively measured ventilation rates of a small greenhouse for several different positions of side and roof ventilators. Again a linear relationship between the ventilation flux and wind speed was found, independent from the wind direction. Temperature differences appeared to be of interest in some cases only, but their effect was soon dominated by the effect of the wind.

1.2 The present research and the organization of the thesis

From the preceding review, it appears that most research on greenhouse ventilation confines itself to the establishment of data and relationships, only applicable to the special greenhouse examined. In many cases, theoretical considerations were not given. Among the few exceptions we have found, the works of Kozai, Sase and Nara [15,16] and Bot [2] seem to be the most important. A research like the present one, which aimed at the development of a general description of ventilation of every Venlo type greenhouse, has to adopt a more fundamental approach and should not be suitable for only one particular greenhouse. Basic principles of the ventilation process have to be recognized and a description has to be made in terms of relevant factors.

Generally, the ventilation through an opening is determined by the pressure difference over the opening and the flow characteristics of the opening. Therefore, knowledge of the flow characteristics of the opening, i.e. the relation between the existing pressure difference across the opening and the volume flux through the opening, is essential to understand and describe the air exchange. Venlo type greenhouses are built as large multi-span blocks with their walls fairly well sealed and their windows mounted on the cover. All greenhouses are equipped with one-side-mounted windows hinged from the ridge which are positioned on the cover in a regular pattern. The air exchange of the greenhouses is regulated by opening and closing the windows to a certain extent. Obviously the flow characteristics of the greenhouse windows are essential for the description of the ventilation flux through the greenhouse cover. In chapter 2 of this thesis, an approach is presented to describe the flow characteristics of one-side-mounted windows as a function of their dimension and window opening. The description is complemented with full scale measurements of the flow through various one-side-mounted windows at different opening angles.

In case of naturally ventilated greenhouses, the driving force for the flow through the windows, i.e. the pressure difference across the window opening, is generated by wind effects or by the temperature difference between the inside and outside air.

In chapter 3, a description is given of the ventilation caused by wind effects through the greenhouse windows, evenly distributed on a 'quasi-infinite' cover. Effects of the wind speed, wind direction and window dimensions on the air exchange through the windows on the cover were investigated. In this chapter, the emphasis was laid on leeside ventilation. In chapter 4, the windward side ventilation and the combined leeside and windward side ventilation are examined. When ventilation is required, usually the leeside ventilators on the cover are first opened to a certain point, depending on the difference between the desired (set point) temperature and the actual temperature. When the leeside ventilators are widely opened and the air exchange is still inadequate to achieve the desired temperature (for instance on a summery day), windward side ventilators are opened too. The moment that the windward side windows join in with the leeside windows is to be preset. One chooses starting with leeside ventilation because of the more equable air infiltration in the greenhouse as compared to the windward side ventilation. In the latter type of ventilation, wind blasts directly into the window (especially in the first span on the windward side) which may cause unwanted local air movement. Given the importance of leeside ventilation as a tool to control the greenhouse climate, the emphasis of the thesis is laid on this type of ventilation.

In chapters 3 and 4, the research on greenhouse ventilation caused by the wind effects was focussed primarily on the air exchange of unbounded greenhouse covers. In chapter 5, results of field measurements of greenhouse ventilation are presented and discussed. The measurements were performed to investigate how the ventilation features of the unbounded greenhouses and those of the greenhouses in actual practise lie in relation to each other. During the measurements reported in chapters 3, 4 and 5, the wind effects strongly dominated the temperature effects. Chapter 6 is concerned with the ventilation due to the temperature effect only and the combined effect of wind and temperature. Experiments are presented on air exchange due to natural convection through rectangular openings and through the opening of a one-side-mounted window. Results of ventilation measurements, during which the buoyancy forces strongly act together with the wind, are evaluated. Final conclusions are drawn in chapter 7.

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2 FLOW CHARACTERISTICS OF ONE-SIDE-MOUNTED WINDOWS

2.1 Introduction

For residences, schools, greenhouses, livestock buildings etc, natural ventilation is an important tool to control the indoor climate. It directly affects factors such as temperature, humidity and composition of the air. These items are of interest with respect to the comfort and well being of the occupants and the energy consumption of the building. To design a building, or to improve the control strategy of the indoor climate, a good understanding of the ventilation features is essential. In view of their importance, ventilation characteristics of buildings and the mechanisms of ventilation were subject of extensive research: e.g. Shaw [1], Dick [2], Foster and Down [3].

In general, when air infiltrates an enclosure through an opening, the pressure difference between the enclosure and the environment can be considered as the driving force for the flow. The volume flux of the air depends not only on the existing pressure difference and the area of the opening, but also on the flow resistance of the opening through which the air has to pass. Though this basic principle is well established, a universally applicable "law of ventilation" is not available. The pressure distributions and the corresponding types of flow near the windows are not only caused by uncorrelated physical aspects such as temperature differences, wind speed and wind direction, but they also depend on a variety of parameters like window type, the location of the windows, shape and size of the building.

By separating the driving force and the flow characteristics of the ventilation opening, the effect of the various parameters can be better understood. When studying the origin of the generated pressure difference, one can distinguish two types of natural ventilation: (a) caused by wind effects or (b) caused by a difference in air temperature between the inside and outside air. Both effects are mutually independent and can be described separately. This will be treated in the next chapters.

The flow characteristic of an opening, relating the volume flux through the opening to the existing pressure difference, is given by the geometry and dimensions of the opening. To be able to calculate the natural ventilation rate of a building, accurate information concerning the flow characteristics of the windows is required. Research on the effect of the inlet configuration on the ventilation is usually directed towards model studies (Smith and Hazen [4], Dybwatt et al. [5], Hopkins and Hansford [6], Egan and Hillickson [7], Timmons and Baugham [8], Timmons [9]). In all these studies fixed opening structures were considered. For many windows however, the window opening areas can be varied by means of some opening component, characterized by the angle with the plane of the wall.

A type of window frequently used for natural ventilation, is the one-side-mounted casement window. Warren [10], investigated ventilation rates of enclosures fitted with this type of window in a windtunnel and in a field experiment. The measurements were performed at different window angles, wind speeds and wind directions. Total effects were studied and no separation between the driving force and the flow characteristics of the window opening was made.

An approach to consider the driving force for ventilation and the flow characteristics of one-side-mounted windows separately, was outlined in the thesis of Bot [11], in which the ventilation of greenhouses was studied. In his approach, the flow generated by a specific pressure difference over the window was related to the dimensions of the window and the window opening angle. His numerical results on the flow characteristics are based on flow experiments in scale models only.

Full scale measurements of the flow through the opening under one-side-mounted windows are an essential supplement of this research to definitely confirm the above mentioned approach. The present chapter resumes, in short, some relevant aspects of Bots thesis and presents full scale measurements of the flow characteristics of windows on a cover of a Venlo type greenhouse. Just for this type of building, with its identical windows distributed evenly on the cover, a knowledge of the flow characteristics of the windows can be applied immediately. With the known flow characteristics of the windows, the effect of environmental conditions such as wind speed and temperature difference between interior and exterior on the ventilation process can be studied.

2.2 Principal considerations

The flow characteristic of an opening relates the volume flux (Φ_V) through the opening to the driving force for the flow, i.e. the existing pressure difference (ΔP).

In the case of air exchange through the opening under a one-side-mounted window, it is obvious that at a given pressure difference the volume flux will vary with the size of the window and with its opening angle. Consequently, this should be incorporated in the general expression for the flow through this type of window opening.

First of all, the flow through a rectangular opening without a flap (fig. 2.1) can be considered. If a pressure difference is maintained over this opening, a stationary volume flux Φ_V will be generated. A relationship between ΔP and the corresponding flux was established by Bot [11] in experiments with scale models. In these experiments, scale model windows (i.e. rectangular openings with different dimensions of length and height) were mounted on a model greenhouse with the same scale factor. Through the windows, an air flow could be generated, from the inside of the greenhouse to the outside, or reverse. For various flow velocities through the window opening, the corresponding air volume flux and pressure drop across the opening were recorded. The Reynolds numbers in the opening were chosen within the same range as those occuring in full scale ventilation ($200 < Re < 21000$). From the experiment, it appeared that for the flow

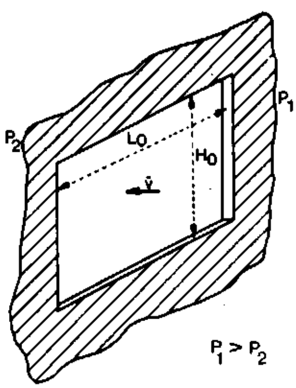

Figure 2.1 Rectangular opening.

region chosen, the viscosity is of minor importance. Consequently, the flow is mainly affected by the density ρ_O of the air and the shape of the opening. This can be expressed in an Euler-like relation:

$$\frac{\Delta P}{\frac{1}{2} \cdot \rho_O \cdot \bar{v}^2} = F_O(L_O/H_O) \qquad (2.1)$$

with:

ρ_O = density of the air in the opening

$\bar{v}$ = average velocity of the air in the opening

L_O, H_O = length and height of the opening respectively.

The aspect ratio L_O/H_O of the opening is defined as the geometric ratio of length over height. The function $F_O(L_O/H_O)$ is called the friction factor of the opening. In the model experiment, this factor indeed turned out to be dependent on the dimensions of the opening only and could be described by:

$$F_O = 1.75 + 0.7 \cdot \exp\,[-\,(L_O/H_O)/32.5] \qquad (2.2a)$$

for $L_O/H_O > 1$

or:

$$F_O = 1.75 + 0.7 \cdot \exp\,[-\,(H_O/L_O)/32.5] \qquad (2.2b)$$

for $L_O/H_O < 1$

In both cases Re must satisfy $200 < Re < 21000$.

When the same opening is considered, but now with a flap mounted on one side of the frame of the opening (fig. 2.2, one-side-mounted window), the friction factor F_W of the opening under the window and the effective opening area A_W depend on the opening angle. Bot now supposed, that this dependency can be represented by two new functions $f_1(\alpha)$ and $f_2(\alpha)$, which relate F_W to F_O and A_W to $A_O = L_O \cdot H_O$:

$$F_W = F_O \cdot f_1(\alpha) \qquad (2.3a)$$

$$A_W = A_O \cdot f_2(\alpha) \qquad (2.3b)$$

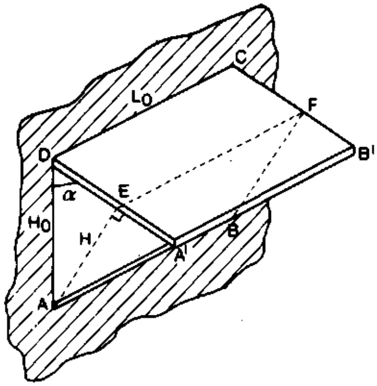

Figure 2.2 One-side-mounted window.

Calling $\bar{v} = \Phi_V/A_W$, we can now reformulate eqn. 2.1 as:

$$\Delta P = F_w \cdot \frac{1}{2} \cdot \rho_o \cdot \left[\frac{\Phi_v}{A_w}\right]^2 \tag{2.4a}$$

or:

$$\text{or } \Delta P = [F_o/f_w(\alpha)] \cdot \frac{1}{2} \cdot \rho_o \cdot \left[\frac{\Phi_v}{A_o}\right]^2 \tag{2.4b}$$

where

$$f_w(\alpha) = [f_2(\alpha)]^2/f_1(\alpha) \tag{2.5}$$

The definition of the window function $f_W(\alpha)$ in this way is preferable to its reciprocal form, since it now approximates zero for $\alpha = 0$ (closed windows).

The function $f_1(\alpha)$, defining the ratio F_W/F_O, can be found when we can establish a value for the friction factor F_W of the opening under the window. For this purpose, for the time being, it is stated that the effective opening area of the opened window equals the smallest area under the flap i.e. area AEFB in fig. 2.2. We notice that in this effective opening area the length and height are $L = L_O$ and $H = H_O \cdot \sin\alpha$.
With this length and height, the aspect ratio of the effective opening adopted is known and can be substituted in eqn. 2.2. So the function $f_1(\alpha)$ can be written according to eqn. 2.3 as:

$$f_1(\alpha) = \frac{F_w}{F_o} = \frac{1.75 + 0.7 \cdot \exp\left[-(L_o/H_o \cdot \sin\alpha)/32.5\right]}{1.75 + 0.7 \cdot \exp\left[-(L_o/H_o)/32.5\right]} \qquad (2.6)$$

Equation 2.6 holds for $L_o/H_o > 1$ or $L_o/H_o \cdot \sin\alpha > 1$. For $L_o/H_o < 1$ or $L_o/H_o \cdot \sin\alpha < 1$, the corresponding relation can be found in a completely analoguous way.

In fig. 2.3 a graph of $f_1(\alpha)$ is given for some aspect ratios according to eqn. 2.6. The figure shows that for small aspect ratios the increase of the function $f_1(\alpha)$ to the value 1 is faster than for larger aspect ratios. For aspect ratios approximating zero and infinity, $f_1(\alpha)$ equals 1 for all opening angles. For a very small split the influence of a flap is clearly negligible, even for very small opening angles!
We want to stress that in general the friction factor is not strongly dependent on the aspect ratio. So an eventual error in the value of the friction factor F_w, resulting from our ad hoc supposition about the effective opening area under the window flap (area AEFB in fig. 2.2, i.e. $L_o \cdot H_o \cdot \sin\alpha$) will not give rise to serious miscalculations in $f_1(\alpha)$ following eqn. 2.6.

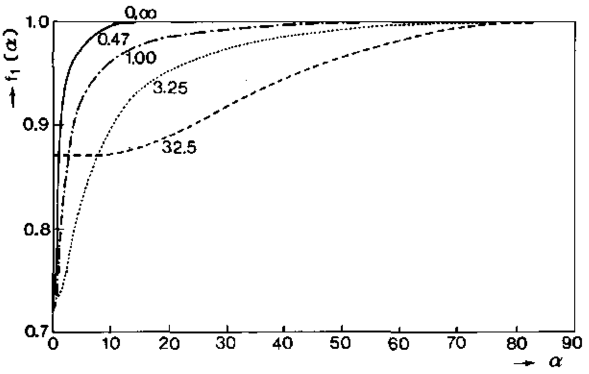

Figure 2.3 The function $f_1(\alpha)$ as a function of the window opening for various aspect ratios.

To establish the function $f_2(\alpha)$, defining the ratio A_W/A_O, the effective exchange area A_W of the opening under the window has to be known or estimated.

Again, we can suppose that the effective opening area is represented by the smallest area under the window i.e. area AEFB in fig. 2.2. In this way the simple function $f_2(\alpha) = \sin\alpha$ could be estimated, relating the exchange area under the window (fig. 2.2) to that without a window (fig. 2.1). It is obvious however, that some contraction will appear in the opening and that the side areas DAE and CBF of the opening (fig. 2.2) will also contribute to the effective exchange opening under the window flap. It seems likely that the side area effect will increase for decreasing aspect ratios. However, a summation of the three areas as the representation of the effective opening area is too simple since it can be expected that $f_2(\alpha)$ will not exceed the value 1. To determine $f_2(\alpha)$ as a function of the aspect ratio, equations 2.5 and 2.4b can be combined to:

$$f_2(\alpha) = [\frac{1}{2} \cdot \rho_O \cdot (F_O/A_O^2) \cdot f_1(\alpha)]^{\frac{1}{2}} \cdot \frac{\Phi_V}{(\Delta P)^{\frac{1}{2}}} \qquad (2.7)$$

This formula implies, that when air volume fluxes and pressure differences are measured for a range of opening angles of windows with different aspect ratios, and therefore different friction factors, values of $f_2(\alpha)$ can be determined experimentally for each specific combination of window and window angle as the quotient of Φ_V over $(\Delta P)^{\frac{1}{2}}$ with the 'correction' factor $[\frac{1}{2} \cdot \rho_O . (F_O/A_O^2) \cdot f_1(\alpha)]^{\frac{1}{2}}$. In this factor, the above mentioned function $f_1(\alpha)$ given by eqn. 2.6 can be incorporated.

2.3 Experimental set up

A compartment (floor area = 6.50 x 6.70 m^2, fig. 2.4) was built in the centre of a Venlo type greenhouse with dimensions 26.6 x 22.2 m^2. The side walls of that compartment were made of blisterpadding mounted on a wooden frame. The compartment was built as air tight as possible. Each of the four windows in the cover of the compartment were constructed in such a way that two different window types, with aspect ratio 1.00 ($L_O = H_O$ = 0.71 m) and 0.47 (L_O = 0.73 m and H_O = 1.55 m) were available (fig. 2.5).

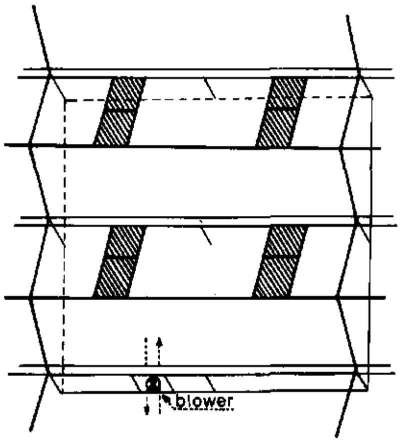

Figure 2.4 Compartment in the centre of the greenhouse.

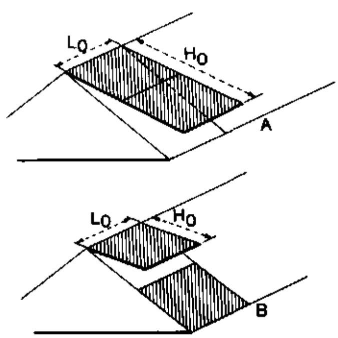

Figure 2.5 Window types on the cover of the compartment.
A: L_0 = 0.73 m, H_0 = 1.55 m; B: L_0 = 0.71 m, H_0 = 0.71 m

In this experiment, the air flow through the window was generated by a high capacity airblower (Nordisk ventilator, type CNA 400) mounted in an opening in one side wall of the compartment. The direction of the air flow could be altered.

To measure the air volume flux, a large tube, with a propeller inside serving as volume flux meter, was mounted at the outlet of the blower. The diameter of the propeller almost equalled the internal diameter of the outlet tube. The volume flux meter, in combination with the blower, was calibrated first in a windtunnel at the IMAG (Institute of Agricultural Engineering, Wageningen). According to Berckmans [12], measured values with this device are dependent on the pressure head over the propeller. Therefore series of Φ_V (air volume flux generated by the blower) and n (rotation velocity of the propeller) were measured at static pressures across the inlet and the outlet of the blower (ΔP_{i-o}) varying from 0 to 40 Pa (fig. 2.6). It is to be noticed that, especially in the case of small air flows, the rotation number of the propeller is influenced by the pressure head ΔP_{i-o}. In our work, as a rule, Φ_V and n were large enough to neglect the influence of this effect.

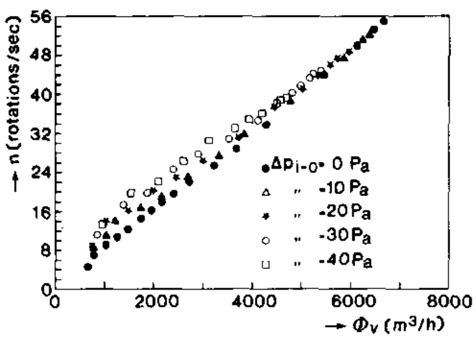

Figure 2.6 Rotation velocity of the propeller as a function of the air flow rate at various pressure heads (ΔP_{i-o}).

During the experiments only one window was opened in the compartment. In this way, it is exactly known how much air is blown or sucked through this window. Moreover, larger pressure differences could be established.

The pressure in the compartment and outside the compartment near the window was sampled by a pressure sensor following Elliott [13]. It consists of a thin circular disk with a diameter of 40 mm and mean thickness of 2 mm, positioned on a long thin stem (fig. 2.7). The sampling ports are located at the upper and lower centre of the disk, sampling static and dynamical pressures local to the disk.

Special attention has been paid to the dimensions of the instrument to eliminate dynamical pressure changes (i.e. dynamic pressure noise generated by the interference between the flow field and the sensor body) at the sampling points. For a detailed description we refer to Elliott [13].

During the experiments, two parallel linked sensors were positioned out-

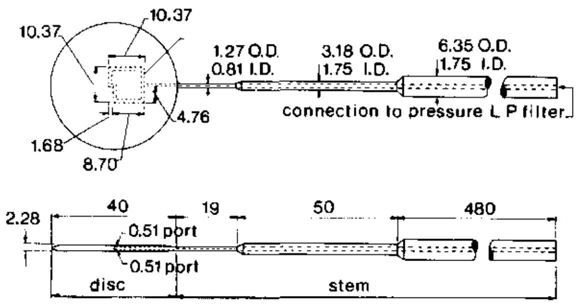

Figure 2.7 Pressure sensor (dimensions are in mm).

side the window out of the main flow generated by the blower. Another pair of parallel linked sensors, the reference sensors, were positioned in the compartment. The sensed pressures were led to a differential micro barometer (Datametrics type 590D) with an operation range of -100 Pa to +100 Pa and an accuracy of 0.05% of the reading. To eliminate high frequency noise in the pressure signal during the measurements, a pneumatic low pass filter with a first order time constant of 70 seconds was placed between all sensors and the barometer. Calibration of the pressure probes and testing of the sensors in combination with the filters and the micro barometer was performed according to Jacobs [14,15].
Moreover, to minimize the low frequency pressure noise due to blast of the wind outside, measurements were performed during periods with low windspeeds, not exceeding 1 m/s.

2.4 Results and discussion

For the window with aspect ratio 0.47, measurements were performed at window openings ranging from 0-14 degrees. For the window with aspect ratio 1.00, the measurements were carried out at opening angles varying from 0-77 degrees. For both window types, the function $f_2(\alpha)$ was determined experimentally from the measured Φ_V and ΔP, according to eqn. 2.7. The results are presented in fig. 2.8, together with some theoretical results (the dotted curves) which will be discussed later.

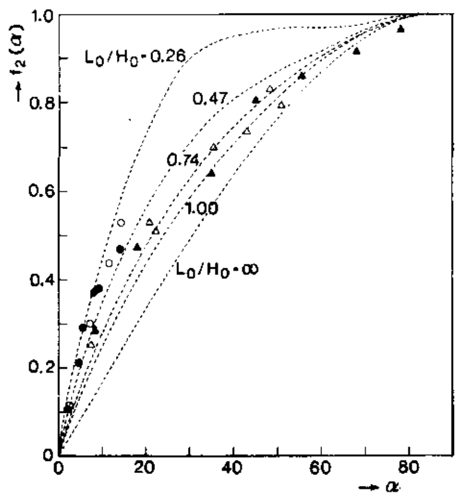

Figure 2.8 Full scale measured values of the function $f_2(\alpha)$ together with a theoretical model (dotted curves) related to the opening angle.

L_o/H_o	1.00	0.47
flow direction inward	▲	●
flow direction outward	△	○

We notice that for windows with lower aspect ratio, at small opening angles, the increase of $f_2(\alpha)$ with increasing opening angle is stronger than for windows with larger aspect ratio. This tendency suggests that somehow the effect of the side areas under the window has to be taken into consideration. The side areas will be relatively more important for windows with lower aspect ratio than for windows with larger aspect ratio.

To interpret these results, we start with our first simple statement, neglecting any side area effect, that $f_2(\alpha) = \sin\alpha$. To determine the additional effect of the side area to the total ventilation, we adopt the considerations of Bot [11]. Looking at the model of fig. 2.9, Bot estimated the part of the side area which remains free to contribute to the total exhange area. Some elementary geometrics then reveals that the effective opening of one side area amounts:

$$\frac{1}{2} \cdot H_o^2 \cdot \sin\alpha \cdot \cos\alpha - \left[\pi \cdot (H_o \cdot \sin\alpha)^2 \cdot \frac{90-\alpha}{360}\right]$$

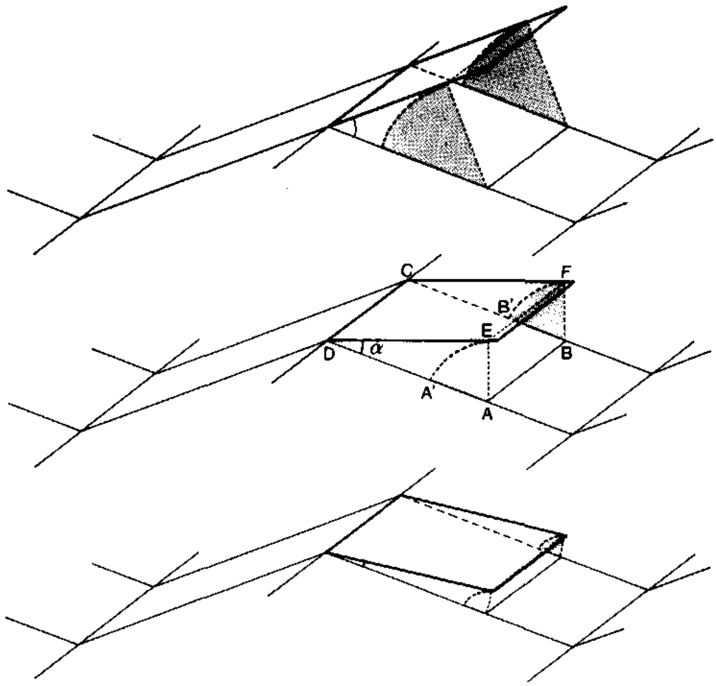

Figure 2.9 Model to describe the effect of the side area.

In order to amount to some possible deviation from this model, Bot still introduced two arbitrary constants a and b, so that his final results for $f_2(\alpha)$ reads:

$$f_2(\alpha) = \sin\alpha \left[1 + a\cdot\frac{H_o}{L_o}\ (\cos\alpha - b\cdot 2\cdot\pi\cdot(\frac{90-\alpha}{360})\cdot\sin\alpha)\right] \qquad (2.8)$$

Scale model measurements reported by Bot gave fair agreement with eqn. 2.8 when a = 0.6 and b = 1.00. The a and b value indicate that the complete circular sections shield off the side areas (b = 1) and that the front areas are more effective for the exchange of air than the shielded side areas (a = 0.6).

Figure 2.8 shows that our experimental results are in full agreement with the geometrical model (represented by the dotted curves) describing the effective exchange area under the window. In the study on the scale models, the flow direction was from the inside to the outside of the model greenhouse. The full scale measurements show that no clear effect on the measured values of $f_2(\alpha)$ can be observed from the flow direction through the window. This implies that the developed expression for $f_2(\alpha)$ holds for both flow directions.

In addition to the obtained values of $f_2(\alpha)$ from the full size experiment, another measured quantity in this experiment supports the similarity of the flow properties in both full size and model windows. In the case of the window with aspect ratio 1.00, which could be opened almost up to 90 degrees, recorded pressure differences over the kinetic energy per unit volume in the opening (according to eqn. 2.1), give relevant information concerning the friction factor F_o of the rectangular opening only.

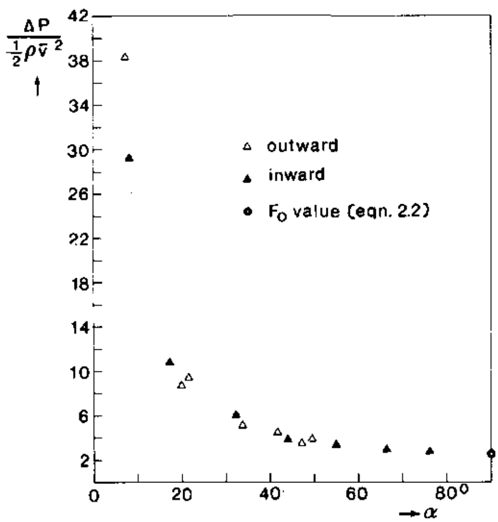

Figure 2.10 Recorded pressure differences over the kinetic energy per unit volume in the opening as a function of the opening angle for the window with aspect ratio 1.00.

Since both functions $f_1(\alpha)$ and $f_2(\alpha)$ approach 1.00 at full opening, the window function $f_W(\alpha)$ will do the same according to eqn. 2.5. Measured values of $\Delta P/[\frac{1}{2}\cdot\rho_o\cdot\bar{v}^2]$ at increasing opening angle will, according to eqn. 2.4b, approximate the F_o value for the rectangular opening with aspect ratio 1.00 at full scale. From fig. 2.10, it appears that the F_o

value, based on eqn. 2.2 and derived from the experiments with scale models, matches well with the full size measurements.

2.5 Conclusions

The performed full size measurements of window parameters of the flow through openings under one-side-mounted windows fit in with previous measurements carried out on similar scale model windows (1:30 and 1:10). The results imply the validity of the developed approach to describe the flow characteristics of these types of window openings for both inflow and outflow. In this approach the ratio between the length and height of the opening, i.e. the aspect ratio, plays an important role. A simple model of the exchange area under the window shows the effect of the side areas for various aspect ratios. The presented description of the flow characteristics can be a useful instrument for predicting the ventilation rate of buildings containing this type of window.

2.6 References

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3 AIR EXCHANGE CAUSED BY WIND EFFECTS THROUGH (WINDOW) OPENINGS DISTRIBUTED EVENLY ON A QUASI-INFINITE SURFACE

3.1 Introduction

In the energy budget of an enclosure, the energy transfer due to the air exchange between the interior and the outside air plays an important role. Physical properties of the inside air such as temperature, relative humidity and composition are directly affected by the ventilation.
Though mechanical ventilation systems are frequently installed for air conditioning, for economical reasons natural ventilation is still an important (or in many cases the only) tool of ventilation used for the control of the indoor climate. Consequently, the proces of natural ventilation is a topic of engineering interest for the thermal design and climate control of buildings such as glasshouses, schools, offices, storage depots et cetera.

The driving force for natural ventilation is the pressure difference across the ventilation openings caused by wind effects or by thermal effects. When the air exchange of the building or structure only depends on natural ventilation, the ventilation due to both the wind and the thermal effects should provide a sufficient air exchange. The mechanisms behind both types of ventilation are mutually independent and can be investigated separately. A study on air exchange due to temperature effects through different openings is presented in chapter 6. The chapters 3, 4 and 5 of this thesis are concerned with air exchange due to wind effects.
When the wind blows over and around a building, the wind field generates different pressures at different locations, which results in a pressure distribution over the building (Dick [1]). In order to simplify the approach, in many procedures it is assumed that a static time averaged pressure P_u (with respect to barometric pressure as a reference) is generated at the different locations, related to the volumetric kinetic energy of the averaged wind field at a reference level, $\frac{1}{2}\cdot\rho_a\cdot\bar{u}^2$, according to:

$$P_u = K_p \cdot \frac{1}{2} \cdot \rho_a \cdot \bar{u}^2 \qquad (3.1)$$

with:

- $\bar{u}$ = average wind speed at reference level
- ρ_a = density of the air
- K_p = dimensionless pressure coefficient, from which the spatial distribution has to be determined empirically.

When the ventilation openings are located at positions with different pressures (i.e. at zones with different pressure coefficients), the averaged static pressure difference between the openings can often be considered as the main driving force for a flow through the enclosure from one opening to another. Then this approach seems suitable and can be used to describe the air exchange.

When, however, only one opening is present in a completely sealed enclosure the above mentioned approach results in a zero-driving force for ventilation, thus resulting in no ventilation at all. The same holds true for the situation in which more openings are located at positions in a surface with the same external pressures P_u. This can be the case when the enclosure, for instance a classroom or an office, only contains the openings in one large wall at which the pressure coefficient K_p is identical at any place. In these cases the fluctuating character of the wind speed and, as a result of this, the fluctuating pressures exerted on the building should be taken into consideration (Hill and Kusuda [2], Cockroft and Robertson [3], Warren [4,5], Narasaki et al. [6]).

The mechanism by which ventilation takes place through one or more openings due to fluctuating external air velocity, is obviously extremely complex and consists of a combination of effects (Malinowski [7]). Dependent on the frequency of the pressure difference oscillations, either pulsating flow or turbulent diffusion will contribute to the air exchange. In the case of two or more openings, the correlation beween the pressures generated at each opening, may result in momentary pressure differences and thus also have an effect on the air flow and air exchange. Most experiments investigating the dynamical character of air exchange, are restricted to ventilation through one or two openings only. To the knowledge of the author, no direct (full scale) measurements have been made in which the air exchange of enclosures due to wind effects through different series of openings in the same plane was studied. In the present chapter, several aspects of the air exchange through openings at comparable positions in a 'quasi-infinite' surface are considered. The term 'quasi-infinite' expresses that, in our set up, the surface edge effects were left aside and that all openings operated under the same geometrical conditions.

In the second section of this chapter, a general description of the acting ventilation mechanisms is presented. The measured ventilation characteristics through the openings are compared with this description. The effects of wind speed, wind direction and number of openings on the air exchange through the surface are studied in sections 3.3 and 3.4. In the ventilation experiments, the cover of a multi-span greenhouse served as the 'quasi-infinite' surface. Usually this type of cover is equipped with one-side-mounted windows positioned in a regular pattern.

In section 3.5, we investigate how the ventilation through these windows on the greenhouse cover is affected by their geometry. Apart from a correct representation of the acting ventilation mechanism, this investigation also requires knowledge of the flow characteristics of the window type involved. An empirical model, describing the flow characteristics of one-side-mounted windows, presented in chapter 2, was employed to evaluate the results of the experiments.

3.2 General approach

The Dutch Venlo type greenhouses represent perfect objects for our investigation. The greenhouses are built as large multi-span units with their walls almost completely sealed and all ventilation windows distributed in a regular pattern on the (saw-tooth shaped) cover. Venlo type greenhouses are usually found to have one-side-mounted windows hinged from the ridge. In most cases, the ventilation windows are opened on the leeside only.

Let us consider an infinite Venlo type greenhouse cover with its windows opened on one side only. Since all openings are located at the same position in the span and the pressure field is identical around each span, the mean pressure due to the wind will be the same at the different window openings. Even so, as the wind has a turbulent character, the momentary pressures over the windows will fluctuate. Bot [8] demonstrated that in this case the ventilation was mainly due to the pulsating indoor-outdoor pressure difference caused by the variations in the wind velocity.

The amplitude of the pressure fluctuations $\tilde{P}_u$ over the windows can be considered as the driving force for the ventilation process. Bot postulated a relationship for this driving force analogous to eqn. 3.1:

$$\tilde{P}_u = K_f \cdot \frac{1}{2} \cdot \rho_a \cdot \bar{u}^2 \qquad (3.2)$$

defining the pressure fluctuation coefficient K_f, which relates the amplitude of the fluctuating pressure over a window opening in the cover surface to the volumetric kinetic energy of the averaged wind field at reference level. The fluctuating pressures near the opening are determined by the local wind field (near the opening), which is affected by the geometry of the cover surface. Therefore K_f also embodies the translation of the wind field at reference level to the wind field near the opening. Since the window opening angle α and also the dimensions of the window determine the geometry of the cover surface, it is expected that K_f is a function of the window type and opening angle α. By the way we remark that both window type and opening angle play a double role in the air exchange through the windows, since they also determine the flow characteristics of the window opening, as will be discussed later.

We ascertain that the amplitude of the fluctuating pressure difference over the window opening acts as the driving force for the ventilation. To determine the corresponding volume flux through the openings we also need the flow characteristics of the openings. Therefore, when studying the ventilation of an enclosure, knowledge of the flow characteristics of the openings is essential.

An expression for the stationary flow characteristics for one-side-mounted windows, such as the windows of the greenhouse compartments considered, was presented in chapter 2. Basically, a translation was developed between the flow through a rectangular opening (fig. 3.1) and a flow through the same opening but now with a flap mounted on the upper edge (fig. 3.2). The flow resistance of the rectangular opening could be formulated in an Euler-like relationship (200 < Re < 21000):

$$\frac{\Delta P}{\frac{1}{2} \cdot \rho_o \cdot \bar{v}^2} = F_o(L_o/H_o) \qquad (3.3)$$

with:

$\bar{v}$ = the averaged velocity in the opening

ρ_o = the density of the air in the opening

L_o, H_o = length and height of the opening respectively.

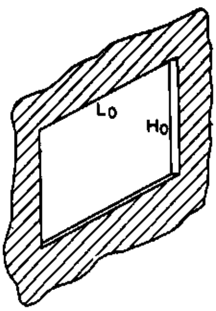


Figure 3.1 Rectangular opening.

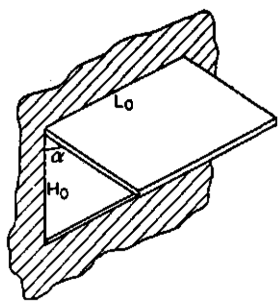


Figure 3.2 One-side-mounted window.

The function $F_o(L_o/H_o)$ is called the friction factor of the opening. Eqn. 3.3 shows that for the given region 200 < Re < 21000 the air flux through the opening was found to be a function of the ratio of the length and height (i.e. the aspect ratio) of the aperture only, independent of the specific Re number. A relation between the existing pressure difference (ΔP) and the corresponding volume flux (Φ_V) through the rectangular opening can be found when eqn. 3.3 is rewritten as:

$$\Delta P = F_o \cdot \frac{1}{2} \cdot \rho_o \cdot \left[\frac{\Phi_v}{A_o}\right]^2 \qquad (3.4)$$

with $A_o = L_o \cdot H_o$, the opening area (and thus $\bar{v} = \Phi_V/A_o$).

For the same opening, but now with a flap (i.e. the window in fig. 3.2), the opening area of the window A_w and the friction factor of the window opening F_w will depend on the opening angle. They can be related to the original opening area A_o and friction factor F_o by means of the functions $f_1(\alpha)$ and $f_2(\alpha)$ as follows:

$$F_w = F_o \cdot f_1(\alpha) \tag{3.5a}$$

$$A_w = A_o \cdot f_2(\alpha) \tag{3.5b}$$

Eqn. 3.4 can be transformed, using eqn. 3.5a and 3.5b, into a relationship between the pressure difference over the window opening and the corresponding volume flux under the window flap:

$$\Delta P = [F_o/f_w(\alpha)] \cdot \frac{1}{2} \cdot \rho_o \cdot \left[\frac{\Phi_v}{A_o}\right]^2 \tag{3.6}$$

with the window function $f_w(\alpha)$ as a combination of the functions $f_1(\alpha)$ and $f_2(\alpha)$:

$$f_w(\alpha) = [f_2(\alpha)]^2/f_1(\alpha) \tag{3.7}$$

When, during a specific period, the air exchange through all the openings together is considered, it can be assumed that no net flow occurs through the cover. Moreover, it can be assumed that the ventilation features of all windows are equal since they all operate under the same conditions.
Furthermore, when we accept as a working hypothesis that the momentary flow direction through a particular window is either inward or outward and that the fluctuating pressure difference over the opening effectively generates a constant ventilation flux, then eqn. 3.2 and 3.6 can be combined taking $\Delta P = \tilde{P}_u$. Realizing that half of the total number of windows is used for inflow and the other half for outflow, this leads to an expression for the inward (and outward) flux through any window:

$$\frac{\Phi_v}{\bar{u} \cdot A_o} = \frac{1}{2} \cdot \left[\frac{K_f(\alpha) \cdot f_w(\alpha) \cdot \rho_a}{F_o \cdot \rho_o}\right]^{\frac{1}{2}} \tag{3.8a}$$

which can be written as:

$$\frac{\Phi_v}{\bar{u} \cdot A_o} = G(\alpha) \tag{3.8b}$$

Eqn. 3.8b states that a linear proportionality exists between the air flux Φ_v and windspeed $\bar{u}$ at reference height for any window opening angle α. The function $G(\alpha)$ combines the flow resistance of the window opening, defined in the window parameters F_o and $f_w(\alpha)$, and the pressure fluctuation coefficient $K_f(\alpha)$ near the windows. Obviously, the ratio (ρ_a/ρ_o) plays a minor role. The function $G(\alpha)$ describes the relation between the ventilation flux per unit window area of the cover surface and the average windspeed at reference level, in dependence of the opening angle α.
The concept of existing fluctuating pressures near the openings not only implies the existence of varying pressure differences over one window opening, but also the possibility of instantaneous pressure differences between different window openings. As the result of these instantaneous pressure differences between the various openings, air flows may be generated between different openings on the cover. This might affect both the ventilation features of the individual opening and the air flux per unit opening area of the whole surface. In this respect, it can be expected that the number of openings, as well as the position of the openings in relation to each other, are of importance.
In our experiments we first investigated whether the air exchange through the cover surface corresponds with the predicted behaviour according to eqn. 3.8. Next, the ventilation characteristics of different compartments with different surface areas (and consequently a different number of openings) were compared. Finally, the effect of the window geometry on the ventilation characteristics was examined.

3.3 Ventilation through a fixed number of openings

3.3.1 Experimental set up

The objective of this study was to investigate the air exchange through a surface with some openings located at positions with the same pressure coefficients K_p.
A situation in which the pressure field is identical around the openings can be assumed when the openings are distributed evenly throughout an

infinite surface. In our experiments, the Venlo type greenhouse cover is used as the surface containing the openings. However, greenhouses, though built in large multi-span units, are not infinite structures. An identical pressure distribution around the window openings can be expected for windows located in the centre of the greenhouse block. Near the side walls of the structure however, additional static pressures will occur and static pressure differences between the window openings in opposite side walls can be expected. These static pressure differences may result in the addition of a continuous ventilation flux superimposed on the effective flux due to fluctuations and can substantially affect the ventilation features of the greenhouse cover.

To avoid this 'side wall effect' in our experiments, the ventilation measurements were performed in fully enclosed greenhouse compartments with their walls relatively far from the outside walls of the whole greenhouse structure. Since the side walls of the compartments were carefully sealed off, the effect of the static pressure differences between the outside walls of the structure on the ventilation features of the compartment were eliminated.

In the present experiment, the ventilation measurements were carried out in some of the 24 identical standard compartments, located in a large glasshouse block (70 x 33 m^2, fig. 3.3), neighboured by identical glasshouses and situated at the Glasshouse Crops Research Station, Naaldwijk, The Netherlands, (Van de Vooren and Koppe [9]). These compartments are equipped with windows with dimensions L_o = 1.46 and H_o = 0.80 m hinged from the ridge on both sides of the span.

The air exchange between any observed enclosure and its environment is often expressed as a so-called ventilation rate. This quantity is defined as the volume flux of air entering (and thus leaving) the enclosure per unit volume of the enclosure, i.e. the total number of complete air changes per unit time. It is usually expressed in air changes per hour. The air exchange rate or ventilation rate R (and so the volumetric air flux through the openings) of an enclosure, can be measured by means of a tracer gas (Hitchin and Wilson [10]).

In our experiments, we apply the decay rate method. In this method a quantity of tracer is released and distributed in the closed enclosure until a

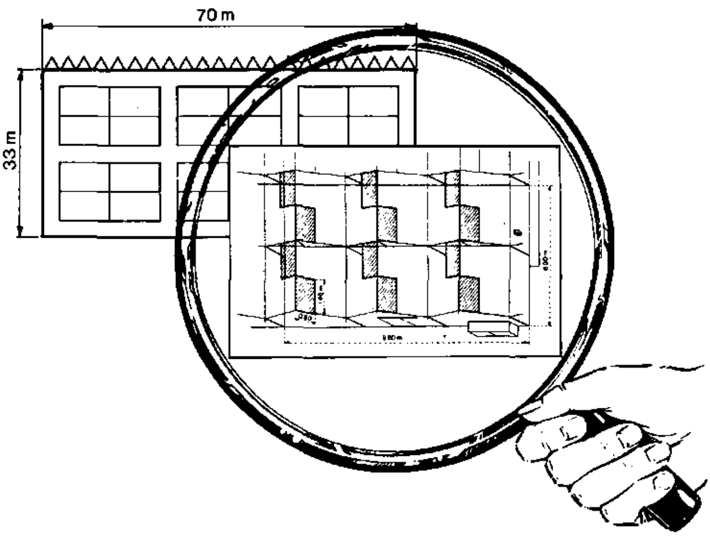


Figure 3.3 Large greenhouse block with 24 standard compartments.

uniform, or nearly uniform, concentration in the enclosure is achieved. After opening the enclosure, the concentration of tracer in the enclosure will decrease due to air infiltration. When we assume the air to be perfectly mixed, this decay will be exponential according to the mass balance of tracer in the enclosure:

$$V \cdot dc/dt = - \Phi_v \cdot (c - c_a) \tag{3.9}$$

thus, for constant Φ_v,

$$\ln [(c - c_a)/(c_i - c_a)] = - \Phi_v/V \cdot t = -R \cdot t \tag{3.10}$$

with:

c = concentration of tracer in the enclosure

c_i = initial concentration of tracer in the enclosure

c_a = ambient tracer concentration

V = volume of the enclosure

Φ_v = ventilation flux

t = time.

By sampling the air on a minute base (relatively fast compared to the decrease), the ventilation rate can be determined from the slope of the graph obtained by plotting $\ln(c-c_a)$ versus time. In all our experiments, the used tracer (N_2O) was blown into the closed compartments and distributed through perforated tubes on the ground surface. The air was sampled at different spatial positions and led to an IR gas analyser.
For a full range of window openings the concentration of the tracer in the greenhouse, the air temperature inside and outside the greenhouse and the mean wind speed and wind direction at reference level of 10 m were measured on a minute base. During the experiments no crops were grown in the compartments.

3.3.2 Results and discussion

In fig. 3.4, a record of the measured tracer gas concentration during one experiment is presented together with its natural logarithm. The linear decrease of $\ln(c-c_a)$ versus time, according to eqn. 3.10, suggests that a continuous effective ventilation flux is found. This despite the fluctuating character of the wind. In fig. 3.5a-d a representative selection from measured leeside ventilation results for some window openings of the standard compartment is shown. The wind direction during the measurements was distinguished into two angles with respect to the window on the cover according to the figure.

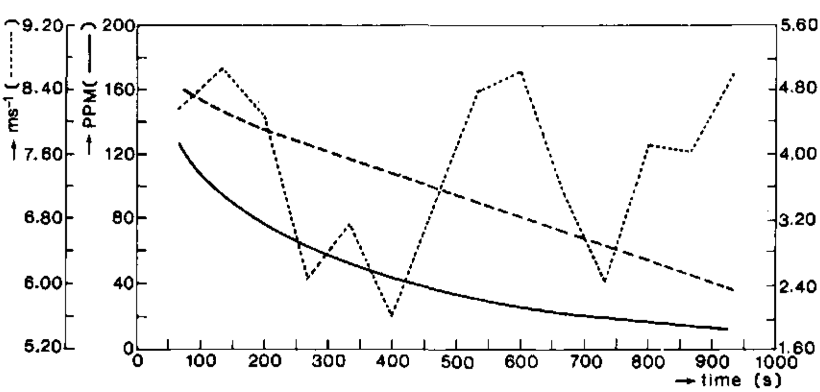
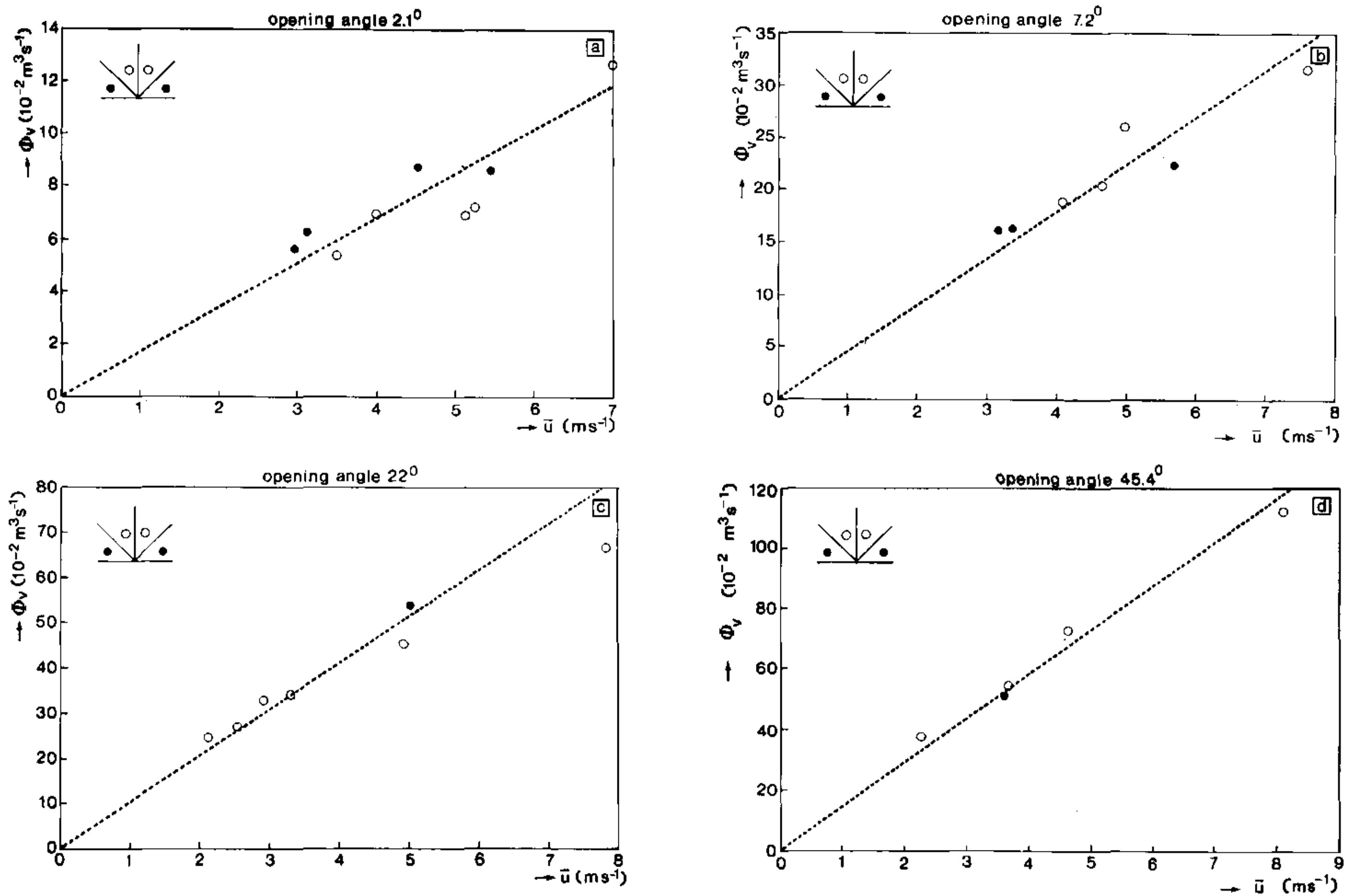


Figure 3.4 Recorded windspeed (ms^{-1}) and tracer gas concentration (ppm) together with its natural logarithm (ln ppm) during one measuring period.



Figures 3.5a-d Ventilation flux in the compartment as a function of the average wind speed at various window apertures. The wind direction is specified according to the figure.

From fig. 3.5a-d a linear relationship between the flux through the openings and wind speed can be observed for various window openings, as was predicted in eqn. 3.8. No unambiguous effect of the wind direction on the ventilation can be noticed. During these ventilation measurements, the compartment was unheated and the temperature difference between the inside and outside air averaged 5 K. The recorded wind speed during all measurements was higher than 2 m/s. Given the results of the study on ventilation due to thermal effects as presented in chapter 6, it can be concluded that in the following experiments the measured air exchange is mainly a result of wind effects.

When the slopes of the ventilation flux - wind speed graphs are plotted against the window opening angle α for all the realized openings we arrive at fig. 3.6. It shows that the compartments are well-sealed since the measured leakage (α = 0°) is close to zero. When the windows are opened up to 15 degrees, the ventilation rises with some approximation in linear proportion to the opening angle. For larger window openings the efficiency decreases. The windows can be opened to a maximum angle of 44°. When we assume that the ventilation flux tends to a maximum value in an approximately exponential fashion, the following function for G(α) can be fitted through the measuring points:

$$G(\alpha) = 2.29 \cdot 10^{-2} \cdot [1 - \exp(-\alpha/21.1)] \qquad (3.11)$$

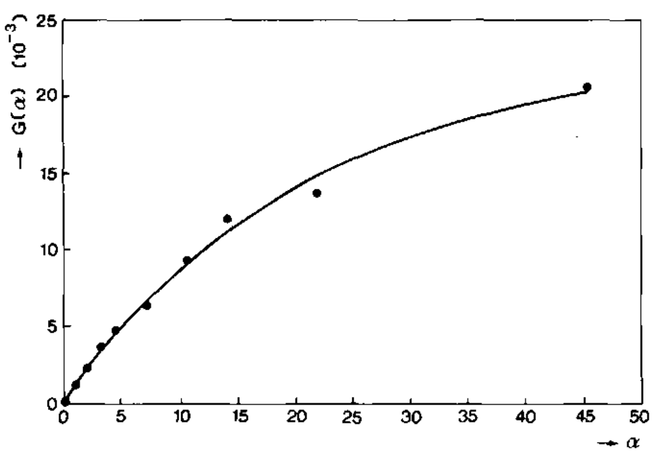


Figure 3.6 Measurements and fit of ventilation flux over wind speed (normalized per unit area of ventilation windows (A_0)) as a function of the window opening.

The results are in agreement with Bot [8] and Nederhoff et al. [11], who measured ventilation rates in the same standard compartments. Nederhoff measured the ventilation for small openings (0-15% = 7°), also using the decay rate method, with CO_2 as a tracer gas. Bot used a static tracer gas method and also measured at window openings up to 44°. In Bot's experiments, the tracer gas was injected continuously with a constant flow into the compartment. Measurements were performed in the equilibrium situation. The static continuity equation then leads to the ventilation flux Φ_v according to:

$$\Phi_v = \Phi_m/(c - c_a) \tag{3.12}$$

with Φ_m = mass flux of injected tracer gas and $c-c_a$ the concentration difference of tracer gas between the inside and outside.

Both eqn. 3.10 and 3.12 are based on a perfect mixing of the inside air. However, the physical volume of the greenhouse compartment may not be the volume participating in the air exchange. The effective volume of the space may be smaller than the physical volume if there are regions of stagnant air (e.g. in the corners). The major advantage of the constant flow method is that the problem of the unknown effective volume does not figure according to eqn. 3.12. On the contrary however, the rather long time needed before equilibrium is reached is a major disadvantage causing difficulties in the application of this method in field experiments. In addition to this, more tracer gas and more sophisticated equipment is required for the experiments.

For the whole range of window apertures ($0° < \alpha < 44°$), the experimental data of Bot are in full agreement with the present data. Bot's data were fitted in a slightly different function, formulated as:

$$G(\alpha) = 1.07 \cdot 10^{-3} \cdot \alpha \cdot \exp(-\alpha/50) \tag{3.13}$$

For increasing opening angles, this latter relation expresses the deviation from a linear relationship between the ventilation flux and the opening angle α. This reveals that the efficiency of larger window openings decreases. When our measuring points are fitted to this function, we find the coefficients $1.03 \cdot 10^{-3}$ and 54.6 respectively. The similarity of the results implies that the effective volume equals the physical volume of the compartment. In these compartments, the decay rate method can be considered to be an appropriate method for inferring the ventilation features.

3.4 Ventilation through different numbers of openings

3.4.1 Experimental set up

To be able to study and compare the ventilation flux through different cover surfaces with different numbers of openings, the corridors of the multifactoral climate greenhouse (fig. 3.3) were converted into five fully enclosed compartments of different size, each with sealed side walls and containing ventilation windows similar to the ones mentioned in section 3.3.

The cover area of these compartments was varied lengthwise (number of spans) and widthwise (width of the span), so that all windows of the compartment were located either at different (successive) spans or at the same span. In this way, three compartments (I, II and III) with a length of 6, 13 and 20 spans and two compartments (IV and V) with one span with widths of 12 m and 27 m (and containing 4 and 8 windows) respectively, were available in addition to the standard compartment (fig. 3.7). The ventilation fluxes through the window openings of the compartments were measured in the same way as described in section 3.3.

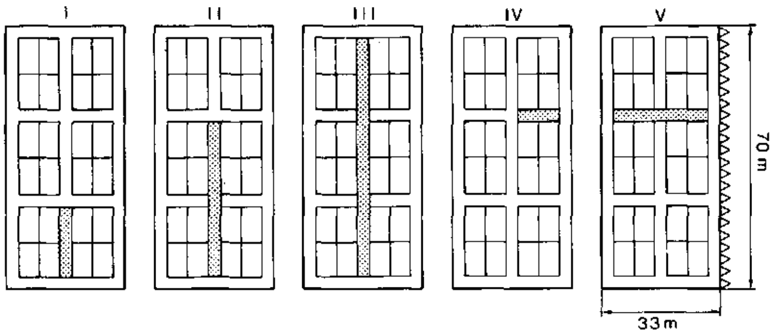


Figure 3.7 Constructed compartments in the corridors of the greenhouse block.

3.4.2 *Results and discussion*

For a comparison of the ventilation characteristics of the different covers, the measured leeside ventilation of the different compartments is represented as values of the function G(α) according to eqn. 3.8b. These values (i.e. the slope of a ventilation flux - wind speed graph) are mostly based on data of three or four decay rate measurements. Again, for all the measurements, no effect of the wind direction on the air exchange could be observed.

Here, analysis of the recorded temperatures and wind speeds in the ventilation experiments also showed that the measured ventilation rates were mainly determined by wind effects. Figure 3.8a shows the measured ventilation fluxes expressed as G(α) for the compartments I, II and III, differing in the number of spans as a function of the window opening angle. For compartments IV and V, differing in width, G(α) is presented in fig. 3.8b. A comparison of the measurements in all compartments, including the standard compartment (VI), is made in fig. 3.8c.

Figure 3.8a shows that the measured leakage ventilation and the ventilation at small window openings of compartments I-III are of the same order of magnitude. For large window opening angles the measured ventilation is more divergent, in addition to which it seems that the ventilation flux of the longest compartment with the highest number of windows is higher. In

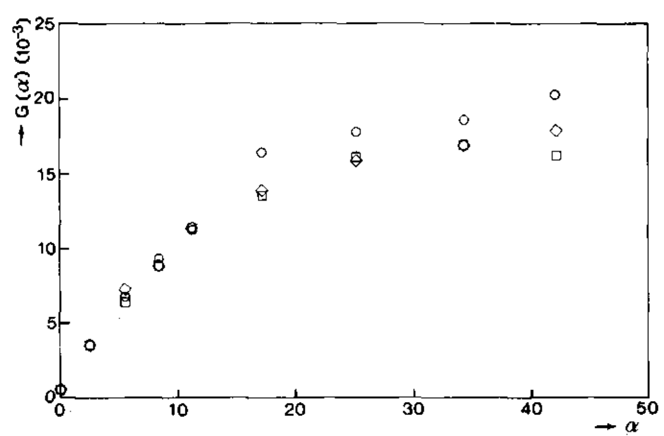


Figure 3.8a Measured values of the ventilation function G(α) for the compartments I-III.
□= compartment I ◇= compartment II ○= compartment III.

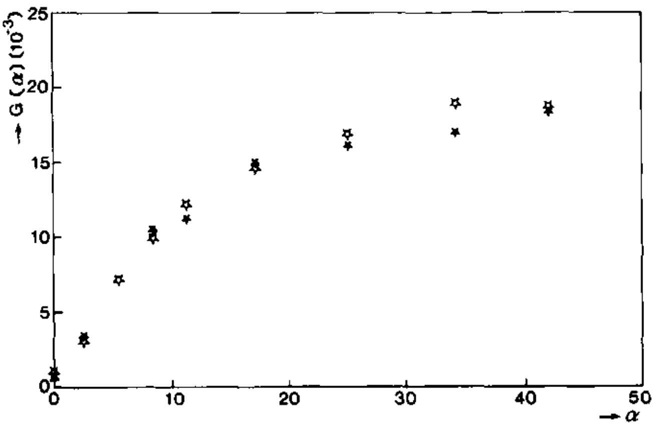


Figure 3.8b Measured values of the ventilation function G(α) for the compartments IV and V.
✱= compartment IV ✡= compartment V

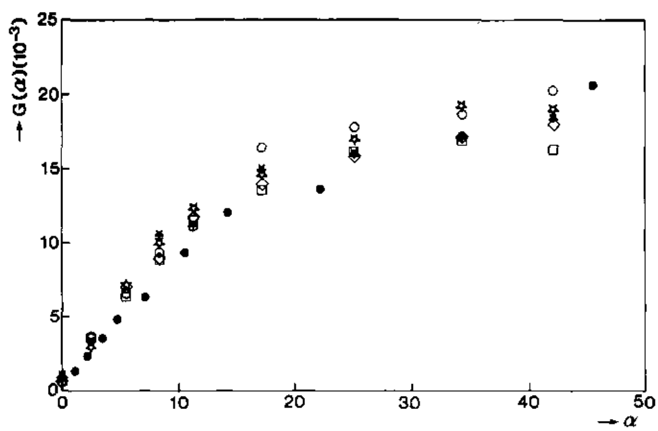


Figure 3.8c Measured values of the ventilation function G(α) for the compartments I-VI.
●= compartment VI, other symbols as indicated in fig. 3.8a and 3.8b.

fig. 3.8b the measured leakage and the ventilation through the opened windows of compartments IV and V do not differ significantly. It can be seen from the figures that the values of the measured leakage in the constructed compartments are higher than the leakage in the standard compartment VI. This is due to the fact that in the standard compartment not only the leaks in the side walls but also the leaks in the cover were sealed carefully and it is this sealing of the cover that was not performed for the compartments I-V in the corridors.

The higher air leakage rate of the compartments I-V may have resulted in an increase of the measured ventilation for all window openings. Indeed, from fig. 3.8c it can be observed that for small window openings the measured air exchange of compartments I-V seems to be slightly higher than the values of the standard compartment.
For larger window openings however, the effect of the leakage on the ventilation is less perceptible, since then the scattering of the measuring points appears to increase. This is the result of the higher measuring of ventilation fluxes at large window openings. The fitting of the exponential decay curve of the tracer in the compartment is then based on a shorter time interval, i.e. less data points during one measuring period. The overall picture of the results shows that no consistent differences in the air exchange characteristics of the compartments of various size can be noticed. Apparently, in this set up, the presence of other window openings in the immediate viscinity does not affect the averaged ventilation flux through the individual window openings. This applies when the neighbouring windows are located on the successive spans or on the same span. These results indicate that there is no correlation between the air exchange through the individual windows and that air exchange through one particular window is mainly driven by the pressure fluctuations over the window in question. The given description of the inflow and outflow through the individual windows, seems to be a correct representation.

3.5 The effect of the window geometry on the ventilation

3.5.1 Considerations

The effect of the window geometry of the one-side-mounted window on the ventilation characteristics through the window opening (eqn. 3.8) is expressed in the window variables F_O, $f_1(\alpha)$ and $f_2(\alpha)$. In eqn. 3.3 and 3.5, which define F_O, $f_1(\alpha)$ and $f_2(\alpha)$, the ratio of the length and height of the window opening appears to be of cardinal importance (chapter 2). To check the effect of the window geometry on the air exchange, experiments are performed for the ventilation through window openings with varying aspect ratios. The function $G(\alpha)$ (eqn. 3.8) for leeside ventilation through windows with aspect ratio 1.825 (L_o = 1.46 m and H_o = 0.80 m) was already experimentally determined in sections 3.3 and 3.4. This data will be discussed in this section in connection with the leeside ventilation measurements through windows with aspect ratio 1.00 ($L_o = H_o$ = 0.71 m) and 0.47 (L_o = 0.73 m and H_o = 1.55 m).

The window variables F_o, $f_1(\alpha)$ and $f_2(\alpha)$ are affected by the aspect ratio. In section 3.2, it was suggested that this also holds for the pressure fluctuation coefficient $K_f(\alpha)$. It is difficult to a priori determine or estimate this effect. However, it can be evaluated afterwards from the measured ventilation functions.

For the window with aspect ratio 1.825 for instance, the function $K_f(\alpha)$ can be calculated with the known flow characteristics (determined from the flow experiments in chapter 2) and the ventilation function $G(\alpha)$ (determined from the ventilation experiments in sections 3.3 and 3.4) according to eqn. 3.8. For that purpose eqn. 3.8 can be rearranged to:

$$K_f(\alpha) = \frac{4 \cdot \rho_o \cdot F_o \cdot [G(\alpha)]^2}{\rho_a \cdot f_w(\alpha)} \qquad (3.14)$$

Also doing this for the other window geometries, the effect of the window geometry on $K_f(\alpha)$ can be evaluated with the opening angle α as a parameter. The measured ventilation function $G(\alpha)$ for the different window geometries was used to compare the ventilation properties of the different windows, since it expresses the average ventilation flux of the algebraic sum of the individual windows at any windspeed.

3.5.2 Experimental set up

The new measurements were performed in an airtight compartment constructed in the centre of a greenhouse block which was mentioned in chapter 2. In this way, disturbances due to the additional static pressures that occur near the outside walls of the greenhouse structure were ruled out as much as possible and the ventilation can be considered to be solely due to the pressure fluctuations over the windows. The cover of the compartment was equipped with one-side-mounted top hinged ventilation windows with either aspect ratio 1.00 or 0.47.

The ventilation flux through these windows was measured by means of the decay rate method, as already described in section 3.3. During the measurements, no crop was present and the compartment was unheated.

3.5.3 Results and discussion

Analysis of the measurements shows that the effect of the temperature difference between the in- and outside air on the total ventilation can be regarded as small, as compared to the wind effect.
According to eqn. 3.8, a linear relationship was to be expected between the recorded wind speed at reference level and the air flux for any window opening and window geometry. This linear proportionality was already confirmed in the ventilation measurements through windows with aspect ratio 1.825 (sections 3.3 and 3.4 of this chapter). In the ventilation experiments, using windows with aspect ratio 1.00 and 0.47, the relation between the wind speed and ventilation flux was again determined for a range of openings.
The results of these latter measurements corroborate the previous findings. For a few opening angles this is illustrated in a ventilation flux-wind speed graph in fig. 3.9. In the calculations, the wind direction in relation to the windows, was classified according to the figure. Despite the scattering of the measuring points, the measurements for the lower aspect ratios seem to show some consistent effect of the wind direction on the ventilation. This effect should be stronger when the windows are opened further. This might be seen when the calculated points of the ventilation function $G(\alpha)$ are plotted against the opening angle for different classes of wind direction (fig. 3.10a,b). The effect of the wind direction was not found for the ventilation through windows with aspect ratio 1.825. It is hard to explain why it should appear for the ventilation with the smaller aspect ratio 1.00 and 0.47. Possibly the eddy size of the turbulent wind in relation to the length of the window (L_o) could be a significant factor in this matter. It could explain that the effect of the wind direction for the windows with aspect ratios 0.47 and 1.00 is of equal magnitude since both windows have almost the same length.

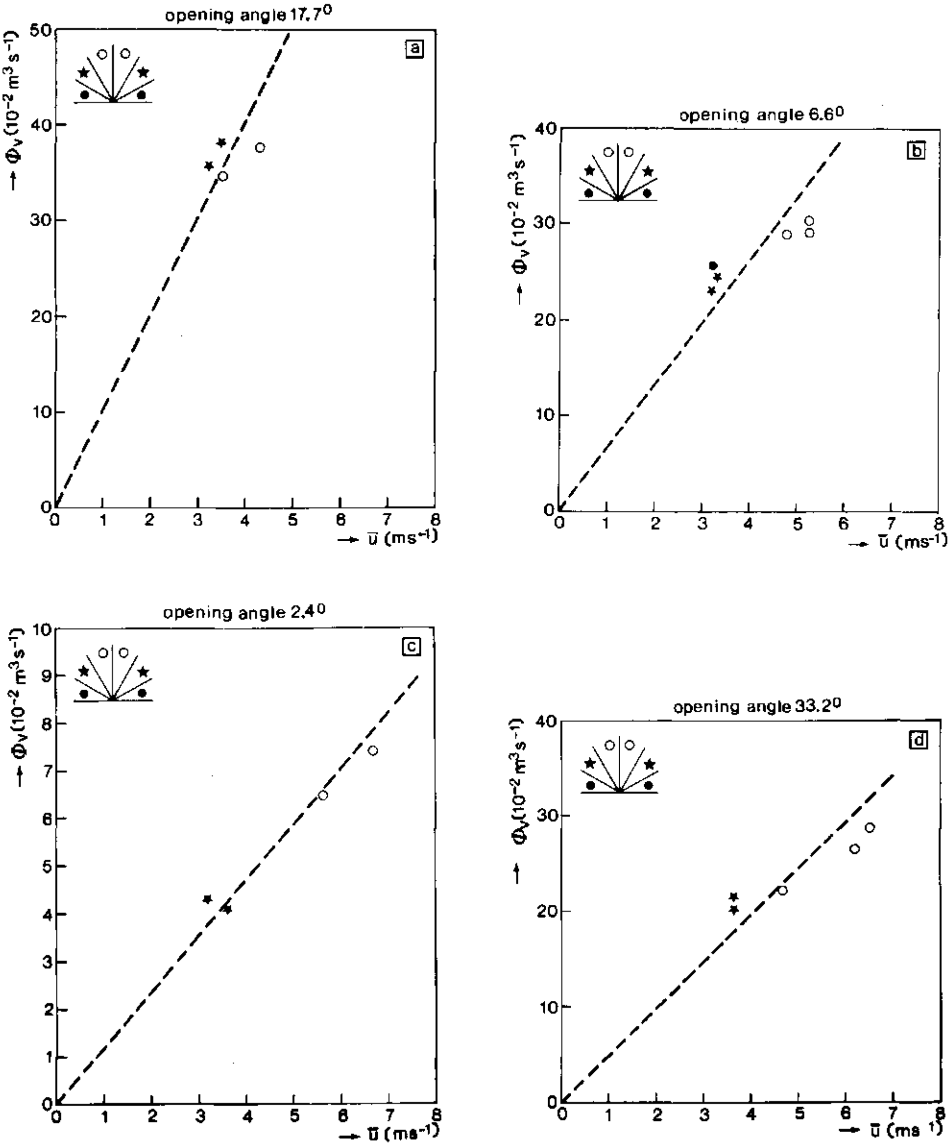


Figure 3.9a-d Ventilation flux in the compartment as a function of the average wind speed. Fig. 9a-b: window type L_0 = 0.73 m, H_0 = 1.46 m. Fig. 9c-d: window type L_0 = H_0 = 0.71 m. The wind direction is specified according to the figure.

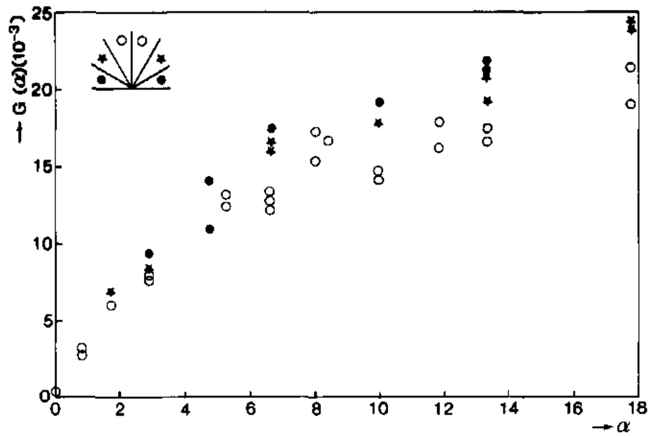


Figure 3.10a Values of the ventilation function G(α) for the window with aspect ratio 0.47. The wind direction is classified according to the figure.

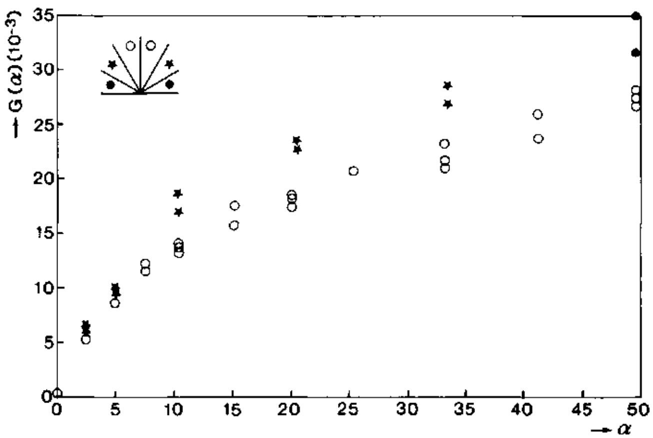


Figure 3.10b Values of the ventilation function G(α) for the window with aspect ratio 1.00. The wind direction is classified according to the figure.

Anyway, more extensive experimental evidence is necessary to obtain definite conclusions.

To compare the ventilation characteristics of the windows, the fitted curves of the ventilation function G(α) of the windows with aspect ratio 1.825, 1.00 and 0.47 are collected in fig. 3.11. For the windows with aspect ratio 1.00 and 0.47 these functions were calculated analogous to eqn. 3.11. However, they were only based on measuring points with the wind direction almost at right angles to the window. The functions for the observed types of windows are found to be:

$$G(\alpha) = 2.62 \cdot 10^{-2} \cdot [1 - \exp(-\alpha/14.6)] \qquad (3.15)$$

for the window with aspect ratio 1.00, and:

$$G(\alpha) = 1.91 \cdot 10^{-2} \cdot [1 - \exp(-\alpha/5.1)] \qquad (3.16)$$

for the window with aspect ratio 0.47.

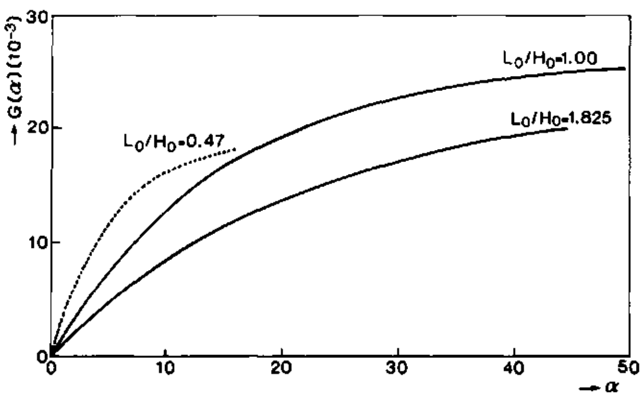


Figure 3.11 Ventilation functions G(α) of the windows with aspect ratio 1.825, 1.00 and 0.47.

Figure 3.11 shows that for the windows with the smaller aspect ratios, the initial increase of the ventilation function G(α) is faster than for windows with higher aspect ratios. This effect can, at least partly, be explained by the flow characteristics of the windows (chapter 2). In particular, the greater effect of the side areas of the windows with smaller aspect ratios should be mentioned.

However, the window parameters F_o and $f_w(\alpha)$ alone, do not fully explain the measured ventilation characteristics of the various windows. From the experimentally obtained ventilation function G(α), the pressure fluctuation coefficient $K_f(\alpha)$ can be calculated according to eqn. 3.14 for the various window types. These pressure fluctuation coefficients $K_f(\alpha)$ are presented in fig. 3.12 for the window geometries under study. When this coefficient was defined in eqn. 3.2, it was already suggested that its value could be affected by the geometry of the surface and (therefore)

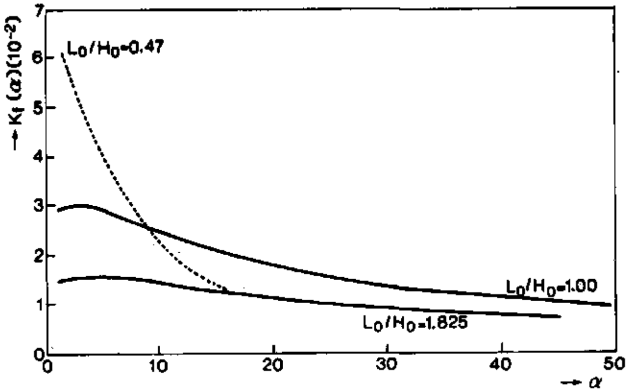


Figure 3.12 The pressure fluctuation coefficients $K_f(\alpha)$ for the windows under study.

also by the window type and opening angle. This seems to be confirmed by our experimental results.

It appears that both the pressure fluctuation coefficent $K_f(\alpha)$ and the flow characteristics of the windows (determined by the window parameters $f_w(\alpha)$ and F_o) play their own role in the air exchange through the windows. The flow characteristics of the window openings are known and are determined by the dimensions of the window and the window opening angle. From the ventilation experiments presented in this section, the pressure fluctuation coefficient $K_f(\alpha)$ is derived for different one-side-mounted windows on a saw-tooth shaped surface. The results indicate that the pressure *fluctuation coefficient $K_f(\alpha)$ is affected* by the window type. Apparantly, the local obstacles on the cover geometry (i.e. the windows) are important contributing factors which determine the local flow field and, consequently, the pressure fluctuation coefficient. Future research is necessary to reveal how the pressure fluctuation coefficient is related to the local flow field and, so, to the geometry of the surface and the dimensions of the window.

3.6 Conclusions

An approach was presented to predict the air exchange through a surface with openings which are located at places with the same mean pressure distribution.

In this approach the amplitude of the fluctuating pressure difference over the openings acted as the driving force for the ventilation. It was postulated that this driving force was proportional to the volumetric kinetic energy of the averaged wind field at reference level. The measured ventilation characteristics, through openings located at comparable places in a 'quasi-infinite' surface, were in full agreement with these predictions. In the experiments, the cover of a Venlo type greenhouse was used as a 'quasi-infinite' surface containing window openings of one-side-mounted windows in a regular pattern. The performed ventilation measurements indicated that the ventilation flux through a number of window openings in such a configuration can be considered as the sum of the ventilation fluxes through the separate openings.
The ventilation features through the openings of the one-side-mounted windows were affected by the geometry of the windows. The experimental results could be partly explained by the flow characteristics of this type of window. However, the measurements also indicated that the pressure fluctuation coeffients, relating the volumetric kinetic energy of the averaged wind field at reference level to the amplitude of the pressure fluctuations near the openings, were not the same for the various windows observed. This difference is caused by the different locations of the windows on the cover surface and their different geometry.

3.7 References

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4 THE WINDWARD SIDE VENTILATION AND THE COMBINED LEESIDE AND WINDWARD SIDE VENTILATION

4.1 Introduction

In actual practice equal growing conditions in the greenhouse are important to achieve a uniform development of the crop. This is the main reason that, when ventilation in the greenhouse is required, the leeside windows should be opened first, since this type of ventilation provides a more equable air infiltration as compared to the windward side ventilation. In the latter type of ventilation the wind blows directly into the opened windows, which may cause undesired local draughts. As a result, the leeside ventilation can be regarded as the most important application of ventilation as a tool in the climate management and therefore has the greatest attention in the present thesis.
However, when the leeside ventilation is inadequate to achieve a desired air exchange, the windward side windows are also opened so as to increase the ventilation flux. To gain insight into the effect of combined leeside and windward side ventilation, quantitative knowledge of this combined mechanism has to be available. To the author's knowledge no ventilation measurements were performed up till now in Venlo type greenhouses, both when the windows were opened on the windward side or when they were opened in combination of the windward side and leeside of the spans. Therefore, an exploratory investigation was performed which will be discussed in the present chapter. At the end of this chapter no pertinent references can be given.

When the windows on the cover are opened on the leeside of the spans only, the pressure fluctuations over the window openings act as the driving force for ventilation. The experiments in chapter 3 indicate that the air exchange through the individual window is determined by the pressure fluctuations over the window opening in question and that it is not affected by the presence of other leeside window openings. However, when the windows are opened on both sides of the spans, an averaged static pressure difference may occur between the windows on the leeside and windward side, which could generate a cross flow between the windows on the opposite sides of the spans. As a result the original leeside (or windward side) ventilation flux through the individual window may now be affected by the presence of window openings located on the opposite side of the span. The arrangement of the windows on the greenhouse cover, in particular the distance between the leeside and windward side window openings on the spans, may be an important factor in this respect. Usually, the windows of Venlo type greenhouses are mounted alternately lengthwise on both sides of the ridge, so that when a window is open on one side of the ridge the glass immediately opposite is fixed. The number of glass panes mounted in between the succesive windows on the ridge varies for different greenhouses.

In the experiments presented in the next section, it was investigated how the combined ventilation is related to the separate leeside and windward side ventilation. It was chosen to perform the measurements in a compartment with the succesive windows on the ridge positioned alternately according to figure 4.1. For such a window arrangement, with a relatively short distance between the window openings on the opposite sides of the spans, a cross flow, if present, may occur more easily.

Looking at the results in section 4.2, it was considered to be of interest to measure the windward side ventilation characteristics of the windows mentioned in the previous chapter, which were mounted on a 'quasi-infinite' cover. The results of these measurements are given in section 4.3.

4.2 The combined leeside and windward side ventilation

4.2.1 Experimental set up

To study the combined action of leeside and windward side ventilation, ventilation measurements were performed in a greenhouse compartment at the IMAG (Institute of Agricultural Engineering, Wageningen, The Netherlands). In fig. 4.1 the geometry and situation of the compartment is given, together with the position of the leeside and windward side ventilators (L_o = 2.00 and H_o = 0.80 m). The figure shows that the compartment is

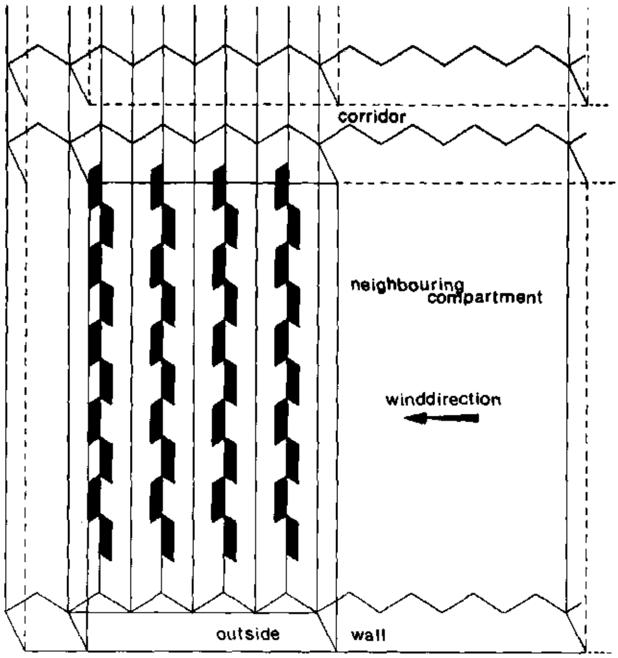

Figure 4.1 Greenhouse compartment (IMAG).

located along a side wall of a greenhouse block. Therefore the cover of the compartment can not be considered as 'quasi-infinite'. The present experiment, however, aims at a comparison of the effect of combined ventilation with that of separate leeside or windward side ventilation. Qualitatively this comparison will not be affected too much by the occurrance of a small side wall instead of a complete 'quasi-infinite' cover.

In the compartment first the leeside and windward side ventilation characteristics were determined separately. Then measurements were performed for a range of simultaneously opened leeside and windward side windows. The ventilation rates were measured in the way described in chapter 3. During the experiments no crop was grown in the compartment and the compartment was unheated.

4.2.2 Results and discussion

The measured ventilation fluxes are represented as the ventilation function $G(\alpha)$ as defined in eqn. 3.8b in chapter 3:

$$G(\alpha) = \Phi_v / [\bar{u} \cdot A_o] \qquad (4.1)$$

with:

Φ_v = ventilation flux

$\bar{u}$ = average wind speed at reference level

A_o = area of ventilating windows

In fig. 4.2, measured fluxes for both the separate leeside ventilation and windward side ventilation are given. All the measurements were performed at the same wind direction, transverse to the line of the ridge. For this wind direction, the wind approached the compartment after having passed at least 13 spans. During the measurements the temperature difference between the inside and outside air was small and the wind speed varied from 3-6 m/s, so the air exchange can be considered to be mainly caused by wind effects.

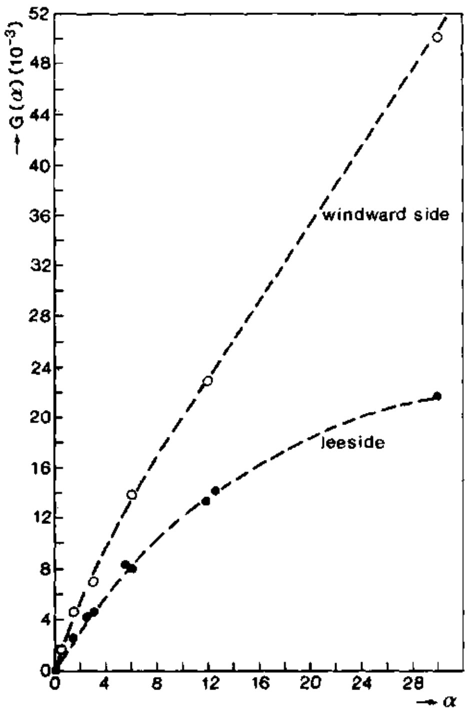

Figure 4.2 The measured leeside and windward side ventilation characteristic of the compartment.

For the leeside ventilation an exponential course is found, comparable to that of the measured leeside ventilation characteristics for a 'quasi-infinite' cover, which have been reported in the previous chapter. The windward side ventilation, however, seems to be almost directly proportional to the window opening angle.

It was already mentioned that the ventilation measurements in this section were not performed in a fully enclosed compartment. Therefore a comparison of the ventilation characteristic of the window type with aspect ratio 2.5 with that of the window types mentioned in chapter 3 is not significant since some effects on the ventilation of additional static pressures near the side wall may occur. The effects of the side walls of the structure on the air exchange will be discussed in chapter 5.

The ventilation function $G(\alpha)$ relates the ventilation flux per unit ventilation window area of the cover surface to the average windspeed at reference level. In case of the combined ventilation, the total window area is doubled. To be able to compare the different types of ventilation, the values of the function $G(\alpha)$ of the combined ventilation will be based on the same window area corresponding to either windward or leeside ventilation.

Measured values of the combined leeside and windward side ventilation are presented in fig. 4.3. In this figure the measuring points are values of the measured ventilation function $G(\alpha)$ for a range of window openings at the leeside (horizontal axis) with, at the same time, a fixed window opening at the windward side. During the experiments, the chosen window openings on the windward side were relatively small. When the windows are widely opened on both sides, very large ventilation fluxes will occur. This generally results in an increase of the scattering of the measuring points, which hampers the interpretation of the results.

In fig. 4.3, the determined leeside ventilation characteristic of the compartment (fig. 4.2) is given as a reference (curve 5). All the measuring points in fig. 4.3 with small windward side window openings of 0.7°, 1.5° and 3° are based on a set of at least two coherent measuring periods. For these window openings, despite the usual scattering of the measuring points, a general trend is noticeable in the figure: the combined ventilation flux seems to be approximately equal to the sum of the separate

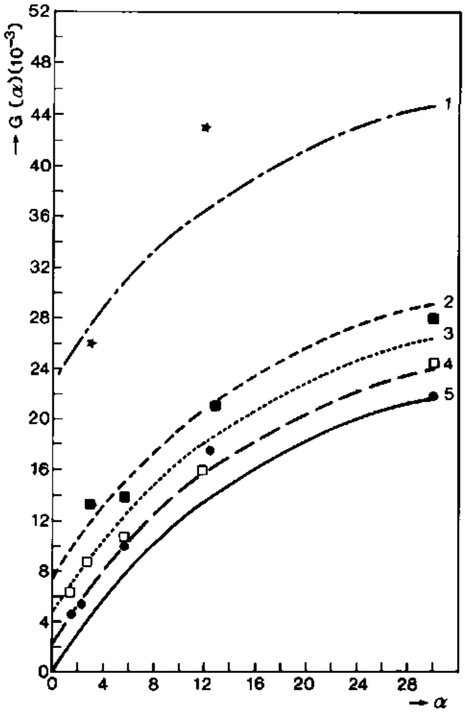

Figure 4.3 The combined leeside and windward side ventilation.

measuring point	fixed opening angle at windward side
★	α = 12°
■	α = 3°
□	α = 1.5°
●	α = 0.7°

The curves 1-5 indicate the sum of the separate leeside and windward side fluxes for fixed windward side openings of 12°, 3°, 1.5°, 0.7° and 0° respectively.

leeside and windward side ventilation fluxes. This is shown in the figure by the dashed curves which represent the calculated sum of the separate leeside and windward side ventilation for the relevant window opening angles at leeside and windward side, according to fig. 4.2. In fig. 4.3, for the largest opening of the windward side ventilators (12°), only two measuring points, each based on one measuring period only, are available.

Despite the smaller reliability of these points, due to the expected large scattering at large window openings, they certainly sooner confirm than contradict the observed trend.

It can be expected that static pressure differences will occur between the leeside and windward side of a span, so between the windows at both sides. However, no clear effect of a possible internally connected flow path between the windows on the ventilation can be observed. For very large window openings on the windward side, however, this could not be reliably investigated due to the very high ventilation fluxes and therefore the short respons times.

The results in this section indicate that both the leeside and windward side ventilation characteristics contain valuable information to understand the combined ventilation as the sum of the individual components. Therefore it was considered to be of interest to measure and present the windward side ventilation characteristics of the fully enclosed compartments equipped with windows with the various aspect ratio of 1.825, 1.00 and 0.47; in addition to the previous chapter, where the separate leeside ventilation was studied for the same aspect ratios. These characteristics describe the windward side ventilation through the windows on a 'quasi-infinite' greenhouse cover. This allows the determination of the combined leeside and windward side ventilation through the various windows on a 'quasi-infinite' cover.

4.3 The windward side ventilation through different window types on a quasi-infinite greenhouse cover

4.3.1 Experimental set up

Windward side ventilation measurements were performed in fully enclosed compartments equipped with different window types with aspect ratio 0.47, 1.00 and 1.825. A description of compartments and windows used in this experiment is to be found in chapter 3. Also for the measuring procedure and the processing of the obtained data, the reader is referred to the previous chapter.

4.3.2 Results and discussion

The results of the measurements of the windward side ventilation through windows with various geometries are presented as values of the ventilation function $G(\alpha)$ in fig. 4.4a-c. In the figures the corresponding leeside ventilation functions $G(\alpha)$ for the transverse wind direction are also given as a reference.

The figures show an increase of the windward side ventilation almost in linear proportion to the window opening angles, except for the very large openings. For small window openings ($< 2^\circ$), the air exchange through the leeside and windward side windows seems to be almost of equal magnitude. This indicates that the pressure fluctuations near the cover surface are, in that case, similar for both the leeward side and windward side.

For the windows with aspect ratio 0.47 and 1.00, an effect of the wind direction on the ventilation can again be noticed. This is in line with the findings in chapter 3, where the leeside ventilation was discussed. Windward side ventilation measurements for the window with aspect ratio 1.825 were performed at one wind direction only. Consequently no effects of the wind direction could be observed for this aspect ratio.

The measurements for the windows with aspect ratio 0.47 and 1.00 (fig. 4a and 4b) show a relatively small difference between the presented leeside ventilation function $G(\alpha)$ and the windward side ventilation for a cornering wind, indicated by the filled symbol ●. In fact, a comparison of the leeside (fig. 3.10a,b, chapter 3) and windward side (fig. 4.4a,b) ventilation at this particular wind direction (almost parallel to the line of the ridge) shows that the air exchange through the windows are almost of equal magnitude, especially for small opening angles.

When the measuring points for the transverse wind direction in the figures 4.4a-c are fitted to the function that expresses the deviation from a linear relationship for increasing opening angles, we obtain the following values for the windward side ventilation functions:

$$G(\alpha) = c_1 \cdot \alpha \cdot \exp(\alpha/c_2) \qquad (4.2)$$

aspect ratio	c_1	c_2
0.47	0.0039	22.3
1.00	0.0024	71.8
1.825	0.0012	211.1

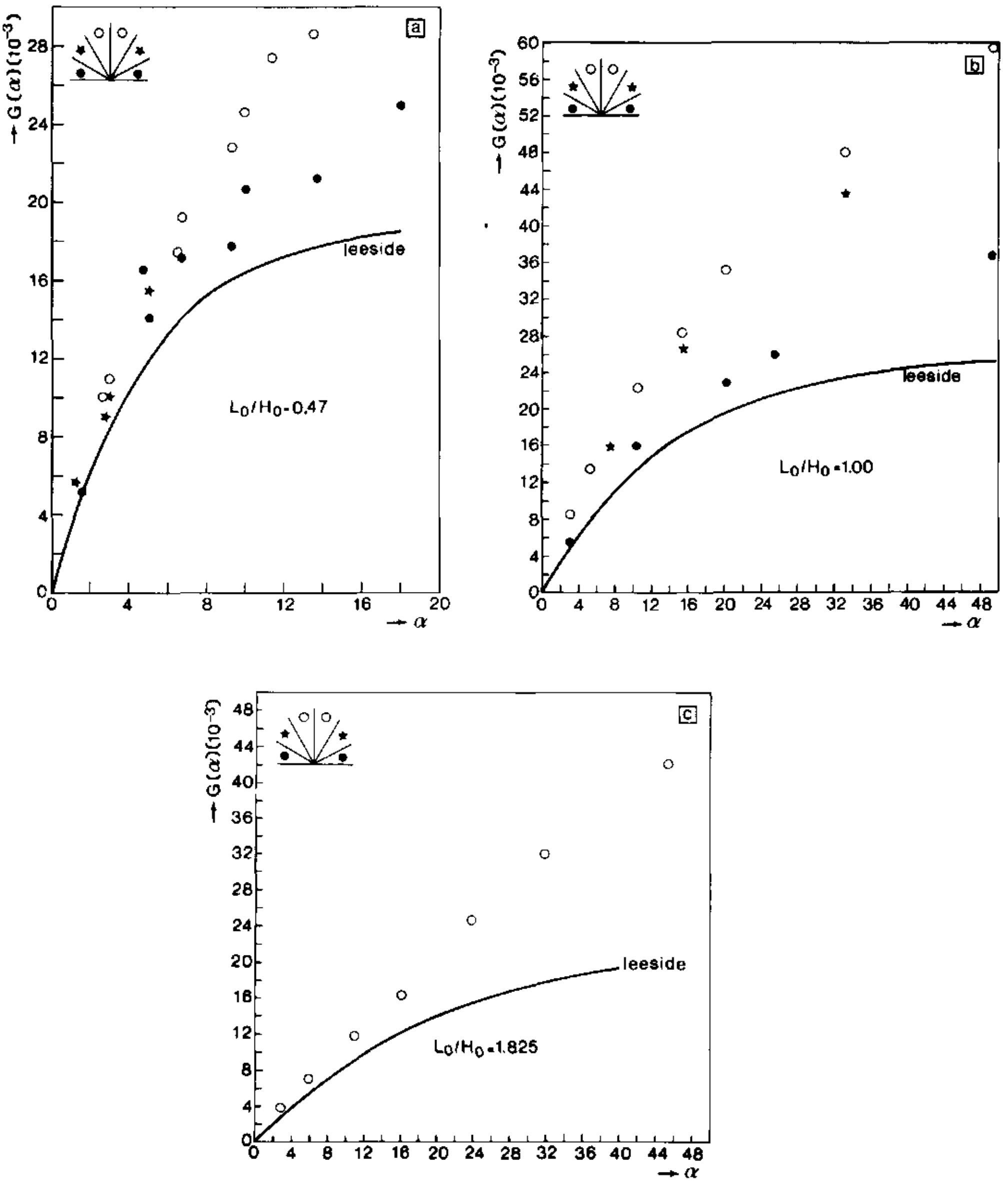

Figure 4.4a-c Values of the windward side ventilation function G(α) for the window with aspect ratio 0.47, 1.00 and 1.825 respectively. The wind direction is specified according to the figures.

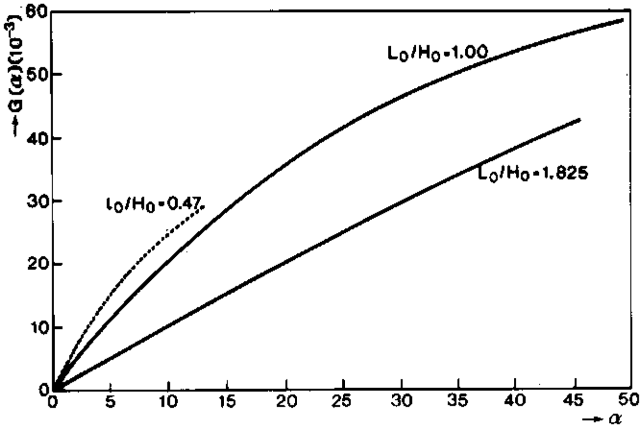

Figure 4.5 Windward side ventilation functions for the windows with aspect ratio 0.47, 1.00 and 1.825.

These functions are given in fig. 4.5. They represent the windward side ventilation functions for the windows mounted on a 'quasi-infinite' greenhouse cover. In common with the already determined leeside ventilation characteristics, the increase of the windward ventilation function G(α), for windows with the lower aspect ratio, is faster than for windows with a higher aspect ratio. This is partly due to the flow characteristics of the different windows. The various pressure fluctuation coefficients $K_f(\alpha)$ for the observed window geometries, are calulated according to eqn. 3.14 in chapter 3 and are presented in fig. 4.6. The figure shows that the

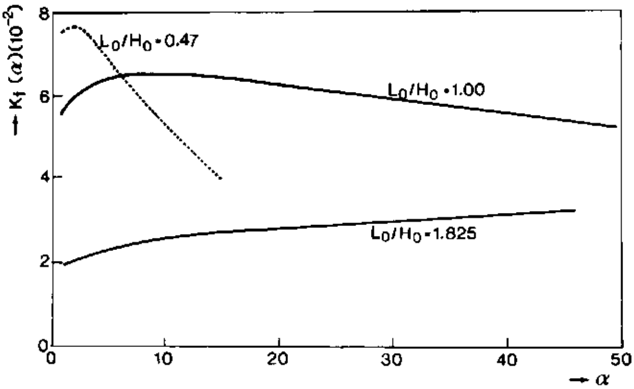

Figure 4.6 The pressure fluctuation coefficient for the windows with aspect ratio 0.47, 1.00 and 1.825 (windward side ventilation).

pressure fluctuation coefficients are very different for the three window types. Like in the case for leeside ventilation, the windward side ventilation characteristic of different window types can therefore not be predicted a priori, even when the flow characteristics of the windows are known. For this purpose a better understanding and more quantitative information on the pressure fluctuation coefficient is needed.

4.4 Concluding remarks

The combined leeside and windward side ventilation was determined in a Venlo type greenhouse compartment and related to the separate leeside and windward side ventilation characteristics of the compartment. The findings of the ventilation measurements indicate that for the transverse wind direction (and for small window opening angles at the windward side up to about 12°) the total flux can be regarded as the sum of the separate leeside and windward side ventilation. No effect of a possible cross flow between the windows on the ventilation flux was noticeable. This observation also indicates that, for the combined window openings, the pressure fluctuations near each opening drive the effective ventilation flux and that the ventilation through a particular window is only dependent on the turbulent effect of the wind at the window opening in question.

In the compartment used for the experiments, the succesive windows on the ridge are positioned alternatively at a short distance from each other. In many greenhouses the distance between the successive windows on the span is larger and an effect of a possibly internally connected flow path between the window openings on the ventilation might be more improbable. An effect of a cross flow between the leeside and windward side windows may occur at large opening angles (i.e. larger than 12° at windward side) of the windows on both sides of the spans or at different wind directions. This could not be investigated.

The separate leeside and windward side ventilation characteristics provide valuable information with respect to the combined ventilation. Therefore windward side ventilation characteristics for various window types on a 'quasi-infinite' cover were determined. For very small window openings

(< 2°) the leeside and windward side ventilation is almost of the same magnitude. The measurements indicate that this also holds for the leeside and windward side ventilation through the windows with aspect ratio 0.47 and 1.00 for the wind direction almost parallel to the line of the ridge.
For the windward side ventilation, different pressure fluctuation coefficients were found for the window types observed. A better knowledge of the pressure fluctuation coefficients for various window types for both leeside and windward side ventilation is needed to predict, a priori, the combined ventilation.

5 FIELD MEASUREMENTS OF GREENHOUSE VENTILATION

5.1 Introduction

Up to now, the research on ventilation caused by wind effects was focussed primarily on the 'quasi-infinite' greenhouses. For these greenhouses it was assumed that an identical pressure distribution occurs around each span and at any individual window and that there are no effects on the ventilation of static pressure differences between the outside gable ends of the greenhouse structure. For this situation an approach was formulated for the air exchange through the one-side-mounted windows. Indeed due to the concerning experiments, valuable insight into the wind induced ventilation was gained. This is relevant for all large multi-span greenhouses. Numerical parameters were collected for Venlo type greenhouses.

However, the step from the fully enclosed compartments in the previous chapters (representing the 'quasi-infinite' cover) to a greenhouse in actual practice is rather drastic. It includes not only the presence of the side walls (and absence of the partition walls of the compartment) but generally also an increase of the cover surface area.
It was already noticed in chapter 3, that an effect on the wind flow and wind-generated pressure distribution around the greenhouse is to be expected, due to the presence of the outside wall of the structure (Phaff [1], Stathopoulos [2]). This effect induces local differences between the pressure distribution around the spans on the cover. It is expected that these differences are most striking around the spans near to the outside walls of the building.
Similar effects on the wind flow and pressures (and consequently on the induced ventilation) can be caused by factors such as the terrain roughness and the density and geometry of buildings surrounding the greenhouse (Wiren [4], Borges and Saraiva [5]).
To investigate these effects, wind tunnel experiments and the use of numerical calculation studies of the wind flow and resulting pressure

distribution are widely recognized as powerful tools (e.g. Mathews [5]). However, a faithful simulation of the air exchange of differently sized greenhouses under various site conditions requires a special and extensive study. This does not fit into the scope of the present study which is primarily confined to the properties of full scale Venlo type greenhouses as such.

The additional wind loads on the structure are determined by the interaction of the wind flow with the building. This interaction depends on the building size and shape and its flow characteristics. Though several investigations have been carried out to study wind loads on low-rise buildings, the great number of possible geometries under all kinds of circumstances precludes any precise and general definition of the occuring static pressure distribution in actual practice.
As far as the author is aware, only two reports on full-scale pressure distribution measurements on Venlo type multi-span greenhouses are available (NNI [6], Wells and Hoxey [7]). In both studies, a consistent load distribution on the third and subsequent spans, including the leeward roof slope of the last span, was found for transverse wind. For the longitudinal wind direction, an identical roof load is found for all spans. According to Wells and Hoxley, this load pattern is already established at a short distance from the windward gable ends. These authors also found a non-uniform distribution of pressure coefficients on the side walls and windward roof slope of the considered greenhouse. In the work of the NNI, only one pressure coefficient is given for each side wall.
These findings support our basic idea that for the 'quasi-infinite' covers, examined in the previous chapters, the static pressures around the spans are the same and therefore that in this case the pressure fluctuations over the windows act as the driving force for the ventilation. It should be stressed here, however, that the term 'quasi-infinite' mainly expresses that possible surface edge effects on the ventilation through the cover were left aside and that the windows on the 'quasi-infinite' covers were operating under the same conditions. This in contrast with the literal sense of the word: (physically) unlimited. Obviously, the surface area of a relatively large multi-span greenhouse in actual practise is

much larger than the surface areas of the 'quasi-infinite' greenhouse covers studied in chapters 3 and 4.

In this chapter it is investigated whether the ventilation properties of relatively large freestanding greenhouses can be understood on the basis of the ventilation characteristics of the 'quasi-infinite' cover. For a greenhouse with a particular geometrical configuration, we expect the effect of the additional static pressures near the side walls to be superimposed over the effect of the pressure fluctuations which is assumed to be characterized by the ventilation function of a 'quasi-infinite' cover.

When the concept of superposition of both effects is correct, the difference between the ventilation of the observed large greenhouses and the 'quasi-infinite' cover can be translated into a 'side wall effect' which is dependent on the surface area and geometrical configuration of the greenhouse. Since the wind direction affects the pressure distribution around the greenhouse structure, the ventilation of the non-infinite greenhouse may also be dependent on the wind direction. To investigate both aspects, greenhouse dimensions and wind direction, measurements of leeside ventilation were performed in Venlo type greenhouses with different geometrical configurations and surface areas. Such data, obtained from ventilation measurements in relatively large greenhouses have not been available up to the present.

5.2 Experimental procedure

Ventilation characteristics of different large greenhouse blocks were determined to study the effect of the cover surface area and building geometry on the ventilation features of the greenhouses. The greenhouses in which the measurements are performed and for which the results are presented in the next section are shown in fig. 5.1. A comparison between the dimensions of the houses shows that in greenhouse II the greenhouse width, in greenhouse III the greenhouse length and in greenhouse IV both greenhouse length and width approximately doubles with respect to greenhouse I. All greenhouses used in the field experiments were undivided, thus having

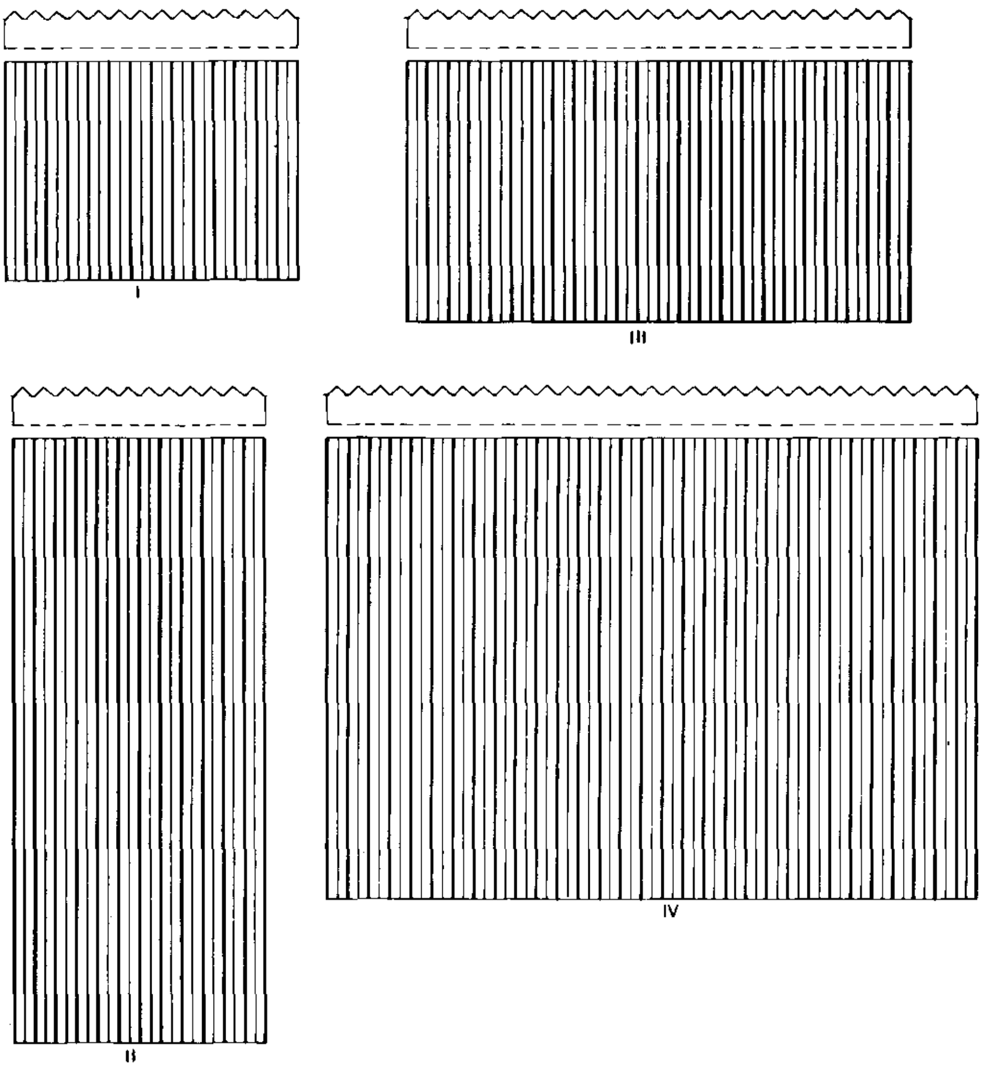

Figure 5.1 Greenhouses for which results are presented in this chapter.
Greenhouse I: length = 44.8 m, width = 32 m, eaves height = 2.73 m, window dimension: L_0 = 2.00 m, H_0 = 0.80 m, number of windows on each side of the span:4.
Greenhouse II: length = 38.4 m, width = 88.3 m, eaves height = 3.35 m, window dimension: L_0 = 2.00 m, H_0 = 0.80 m, number of windows on each side of the span: 11.
Greenhouse III: length = 76.8 m, width = 39 m, eaves height = 3.31 m, window dimension: L_0 = 1.46 m, H_0 = 0.80 m, number of windows on each side of the span: 6 or 7.
Greenhouse IV: length = 98.1 m, width = 69.25 m, eaves height = 2.75 m, window dimension: L_0 = 1.46 m, H_0 = 0.80 m, number of windows on each side of the span: 11 or 12.

four outside walls and no partition walls. Only (as is usual for larger greenhouses in the Netherlands) the greenhouse with a surface area of 6790 m^2 (greenhouse IV) has a farm depository built on one side wall.
The houses in this section were also selected for their exposure to the wind. They were located in the open country with almost no obstructions within 50 m, well exposed to prevailing winds.
The ventilation rates of the greenhouses were determined basically in the same way as described in the chapters 3 and 4. The tracer was distributed in the greenhouses by means of a blower and a system of perforated tubes at soil level. The sampling points (varying from 6 to 9) were equally spaced in the greenhouse and connected by tubing to a manifold and then to the gas analyser. After the release of tracer was stopped, the blower (and in greenhouse II and IV also the fans of the installed hot-air heaters) were left on to provide adequate mixing of the tracer gas with the greenhouse air.
When a constant (averaged in time) concentration of tracer was measured, the blower (and fans) were switched off and the windows were opened. When the windows were opened to the desired position, the recording of the data was started on a minute base. All ventilation measurements were performed in unheated greenhouses without crop.

5.3 Results and discussion

The measured leeside ventilation in the greenhouses is expressed by the ventilation function $G(\alpha)$ according to eqn. 3.8b in chapter 3. This function relates the ventilation flux per unit window area at any wind speed to the opening angle of the windows. The normalization of the ventilation per unit window area enables us to compare the ventilation of the different houses. Also the effect of an unequal number of windows on each side of the spans (greenhouse III and IV) has been taken into account.
The wind direction during the measurements is classified according to the diagram in the figures. All the measurements in the large greenhouse IV were recorded at a particular wind direction by which the farm depository was situated under the lee of the greenhouse. For this wind direction,

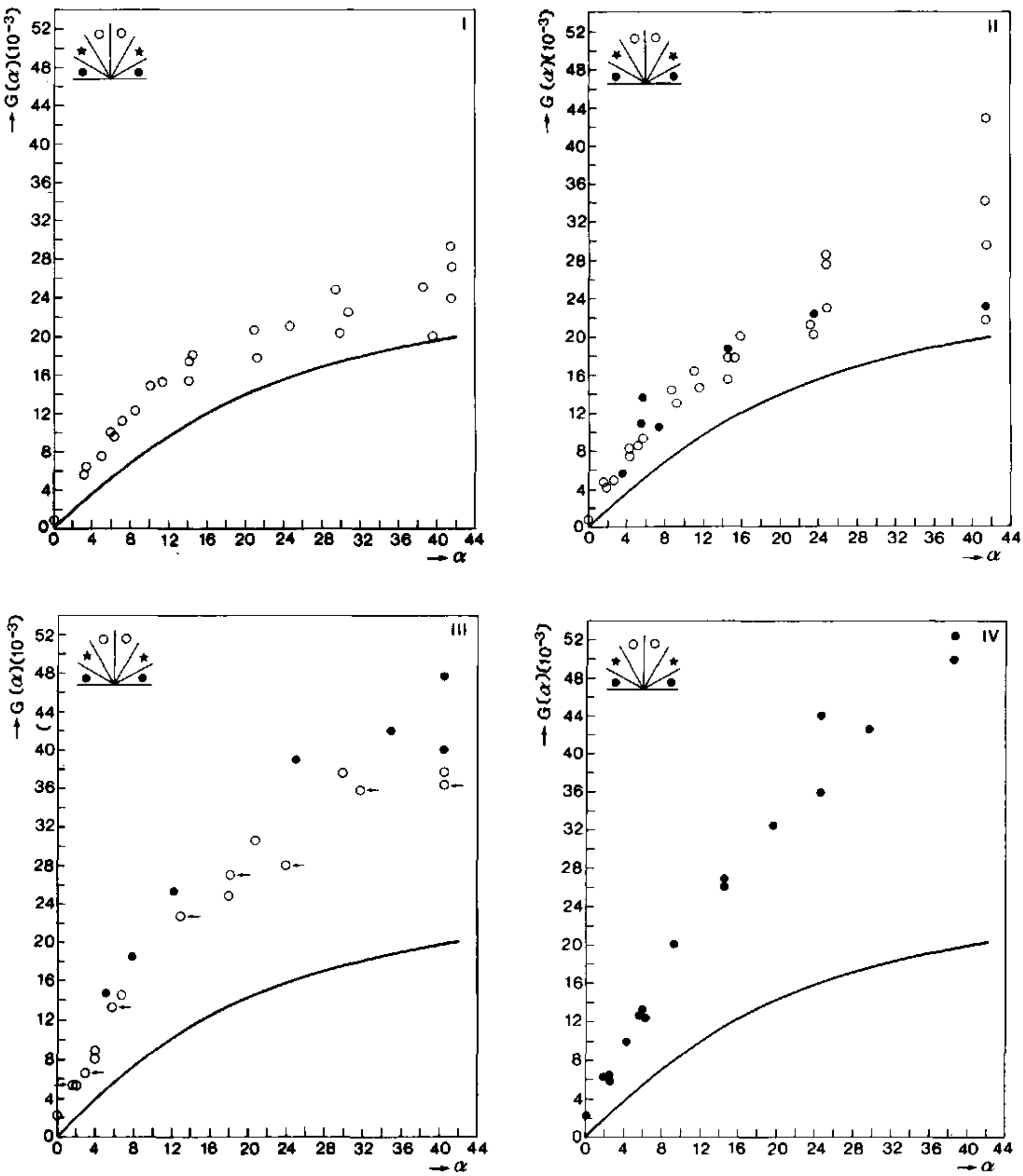

Figure 5.2 Measured values of leeside ventilation for greenhouse I-IV respectively. The wind direction is specified according to the figures. The measurements in greenhouse III (fig. 5.2c), carried out when 7 windows are opened on each span, are marked with an arrow. The full curve represents the 'quasi-infinite' cover.

eleven windows are positioned on the leeside roof slopes. Also for greenhouse III, a distinction can be made between the number of opened windows during the measurements. Measurements carried out when seven windows are opened on each span are marked according to fig. 5.2c.

The measured ventilation functions for the different greenhouses are presented in fig. 5.2a-d. Since the window dimensions of the standard compartments in chapter 3 are similar to those of the windows of the presently considered greenhouses (L_o = 1.46 and 2.00 and H_o = 0.80 m), the ventilation characteristic of the standard compartment (representing a 'quasi-infinite' cover) can well serve as a reference for the measured ventilation of these greenhouses. Therefore, for all greenhouses, the ventilation characteristic of the enclosed standard compartments is given in the figure as a reference.

Leakage ventilation

From fig. 5.2, a relatively high leakage may be observed for the greenhouses III and IV. The greenhouses I and II seem to be more airtight. In general, the effect of the leakage on the ventilation characteristic of a building is very much dependent on the position of the leakage points in relation to the occuring pressure distribution around the structure. Moreover, leakage ventilation, resulting from a poor closing of the windows will be included in the ventilation through the windows when these windows are opened. Since (fig. 5.2c,d) the measured ventilation at very small window openings ($\alpha = 2°$) is substantially larger than the ventilation with closed windows ($\alpha = 0°$), it can be concluded that the leakage ventilation of greenhouse III and IV is not caused by the poor closing of the greenhouse windows but is due to the presence of leakage points distributed elsewhere on the building surface.

The experimental results of the combined leeside and windward side ventilation measurements in the previous chapter indicated that the combined ventilation equals the sum of the separate leeside and windward side ventilation, at least for small window openings at the windward side. The ventilation through the individual window openings is mainly dependent on the turbulent effect of the wind at the openings only. These results suggest (also for the reason that the leakage is relatively small compared to the ventilation through the window openings), that the measured total ventilation of the greenhouses is also the sum of the background leakage component and the ventilation component through the windows. Consequently, the ventilation characteristic of the windows only (i.e. the ventilation characteristic of a greenhouse without leakage) can be obtained by substracting the leakage ventilation from the measured total ventilation.

Wind direction

For greenhouse II and III, leeside ventilation measurements were performed at different wind directions. Though the magnitude and distribution of the wind pressures will be affected by the direction of the wind relative to the structure, the results of the ventilation measurements do not show an unambiguous effect of the wind azimuth on the leeside ventilation. For greenhouse III, a small effect of the wind direction on the air exchange seems to be perceptible. It may be concluded, nevertheless, that the measurements in both greenhouses indicate that there is no important effect of the wind direction on the ventilation.

Greenhouse geometry

Figure 5.2 shows that the leeside ventilation of the houses has increased compared to the measured leeside ventilation of a 'quasi-infinite' greenhouse cover. To interpret the numerical results, we adopt the considerations in section 5.1 and assume that the total ventilation is mainly the resultant of the combined effect of the extra pressure components near the side walls and the pressure fluctuations. When both effects are superimposed we can formulate:

$$\Phi_{v,G} = \Phi_{v,C} + \Phi_{v,S} + \Phi_{v,L} \tag{5.1}$$

where

$\Phi_{v,G}$ = total ventilation of the greenhouse

$\Phi_{v,C}$ = ventilation through the greenhouse cover caused by pressure fluctuations only. It is assumed that this flux through the cover can be characterized by the ventilation function of the 'quasi-infinite' cover.

$\Phi_{v,S}$ = supplementary ventilation due to 'side wall effect'

$\Phi_{v,L}$ = leakage ventilation

In fig. 5.2 the terms in eqn. 5.1 are all expressed as values of the ventilation function $G(\alpha)$ (and thus normalized per unit windspeed and window area). According to the definition in eqn. 5.1 the supplementary ventilation (also expressed as value of $G(\alpha)$) can be obtained from fig. 5.2. For the houses I-IV the supplementary ventilation is given in fig. 5.3. It represents the 'side wall effect' on the ventilation of the whole greenhouse. For larger window openings, the values for the magnitude of this effect will become less reliable due to the increased scatter of the measuring points.

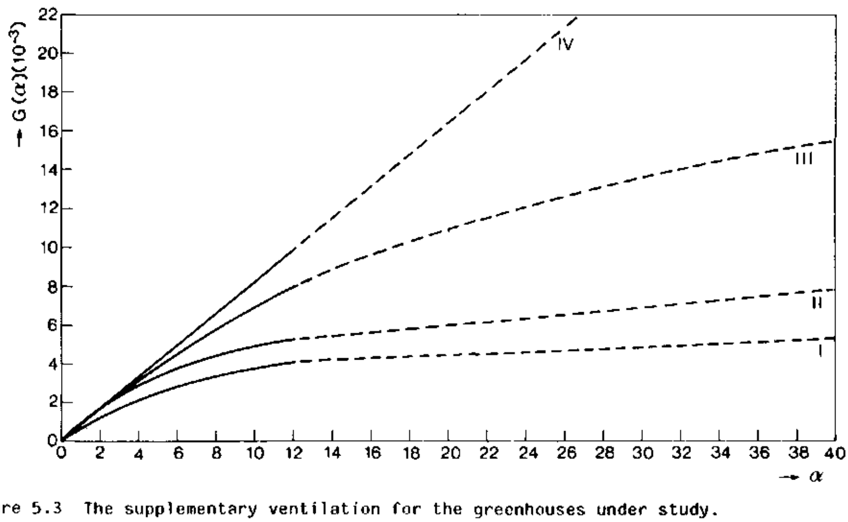

Figure 5.3 The supplementary ventilation for the greenhouses under study.

It is striking that for greenhouse I, with a relatively small surface area, the 'side wall effect' is not very marked while for the other greenhouses the effect on the total greenhouse ventilation is more pro-

nounced. This contradicts the expectation that a surface edge effect (here 'side wall effect') is large for small greenhouses.
From the curves in fig. 5.3 the supplementary ventilation flux $\Phi_{v,S}$ (per unit wind speed) can be calculated. For the various greenhouses, calculated values of $\Phi_{v,S}/\bar{u}$ for opening angles up to 10 degrees are presented in fig. 5.4a,b as a function of the building scale. In fig. 5.4a the perimeter is chosen to characterise the building scale; in fig. 5.4b the surface. The calculations are restricted to relatively small opening angles to minimize errors due to the scatter of the measuring points. Moreover, for small opening angles the possible influence of wind direction on the leeside ventilation is expected to be small (fig. 5.2b,c).

Figure 5.4 shows that the supplementary flux is strongly related to the dimensions of the greenhouse and decreases when the greenhouse becomes smaller. Extrapolation of the trend in fig. 5.4a,b suggests that for very small greenhouses the ventilation characteristic approximates the ventilation characteristic of the 'quasi-infinite' cover. In other words: the effect of the additional pressures near the outside walls can be considered to be small for small greenhouses. Why the relative effect of the supplementary flux on the total ventilation should increase for the larger greenhouses is not yet evident.
When the wind meets the greenhouse, a stagnation zone is created on the upwind wall. The cushion of pressure diverts the flow ahead of the building so that it passes around the sides and over the building. The flow escapes and separates with increased speed, thus reducing the static pressures. Consequently recirculating flow zones are created that cover the downwind surfaces (cover, sides and leeward wall) of the building (ASHRAE [8]). Obviously, the streamline pattern and surface pressures are strongly influenced by the turbulence of the approaching wind and by the building shape. The upwind wall has a finite dimension perpendicularly to the stream direction; this finite dimension is the more manifest when the cover becomes more extended in the stream direction.
Though the geometries of the greenhouses II and III are very different, the measured supplementary flux is almost of equal magnitude. This indicates that the supplementary flux is the result of an effect which is

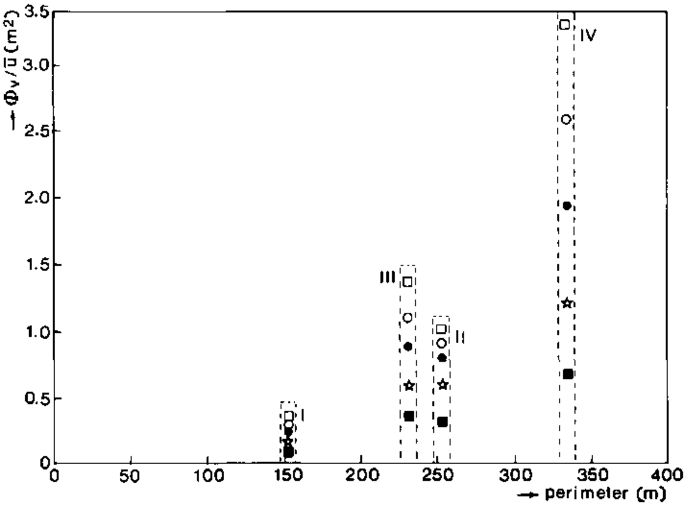

Figure 5.4a The supplementary flux per unit windspeed as a function of the perimeter of the greenhouse, ■ $\alpha = 2°$, ☆ $\alpha = 4°$, ● $\alpha = 6°$, ○ $\alpha = 8°$, □ $\alpha = 10°$.

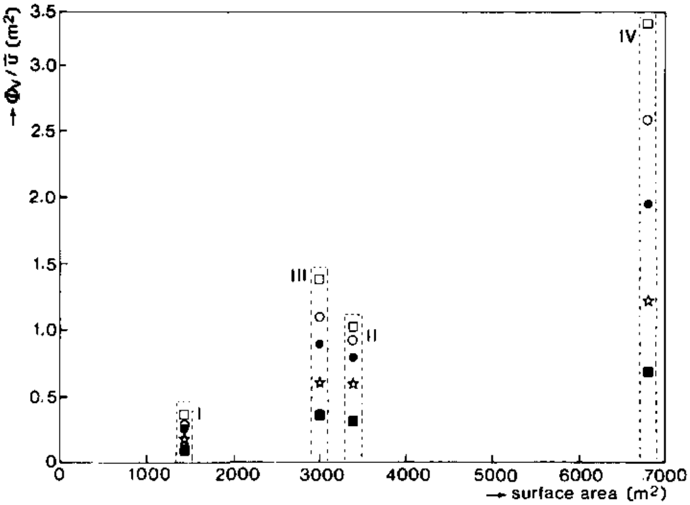

Figure 5.4b The supplementary flux per unit windspeed as a function of the surface area of the greenhouse, ■ $\alpha = 2°$, ☆ $\alpha = 4°$, ● $\alpha = 6°$, ○ $\alpha = 8°$, □ $\alpha = 10°$.

related to the dimensions of both the upwind wall and downwind surfaces. Those dimensions seem to be important parameters with respect to the magnitude of the supplementary flux. This might also explain the fact that no clear effect of the wind direction on the ventilation was perceptible.

In eqn. 5.1 the supplementary flux $\Phi_{v,S}$ was defined as the difference between the measured flux through the cover of an airtight greenhouse and the flux through the same greenhouse cover assuming that the ventilation characteristic was similar to that of a 'quasi-infinite' cover.
A graphic way to account for this supplementary flux (per unit wind speed) for various greenhouses is to represent the actual greenhouse as a quasi-infinite-cover-greenhouse with the same ventilation. Clearly, the quasi-infinite-cover-greenhouse is larger than the actual one. Of course the extension of the surface area has the same window to cover ratio A_o/A as the original greenhouse. This graphic way enables us to compare the supplementary flux of various greenhouses with different window types. While the ventilation through the quasi-infinite-greenhouse-cover is characterized by the ventilation function $G(\alpha)$, we can formulate an expression for the additional surface area A_a:

$$A_a = (\Phi_{v,S}/\bar{u}) \;/\; [(A_o/A) \cdot G(\alpha)] \qquad (5.2)$$

In table 1, the additional surface area A_a for window opening angles up to 10 degrees is calculated for the greenhouses I-IV.

Table 1. Additional surface area A_a (m^2) for the greenhouses I-IV.

opening angle	2°	4°	6°	8°	10°	average
greenhouse I	800	738	714	698	686	727
greenhouse II	2560	2379	2286	2118	1905	2250
greenhouse III	2372	2214	2350	2338	2437	2342
greenhouse IV	5100	5816	5872	6139	6182	5822

It appears that the calculated values of A_a are not too much affected by the window opening. This allows us to calculate an average value for the surface area A_a for opening angles up to 10 degrees. While greenhouse II and III have a comparable A_a, the additional area can be translated into a stroke along the greenhouse with width w (fig. 5.5). This width can be calculated according to:

$$A_a = (p \cdot w) + 4w^2 \qquad (5.3)$$

where p is the perimeter of the greenhouse.

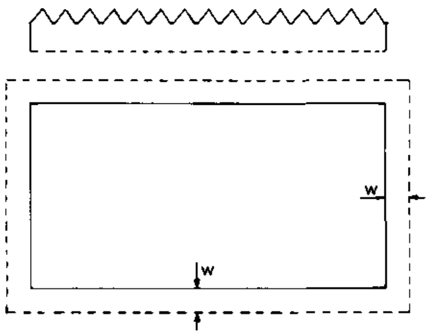

Figure 5.5 The extension of the original surface area along the sides of the structure.

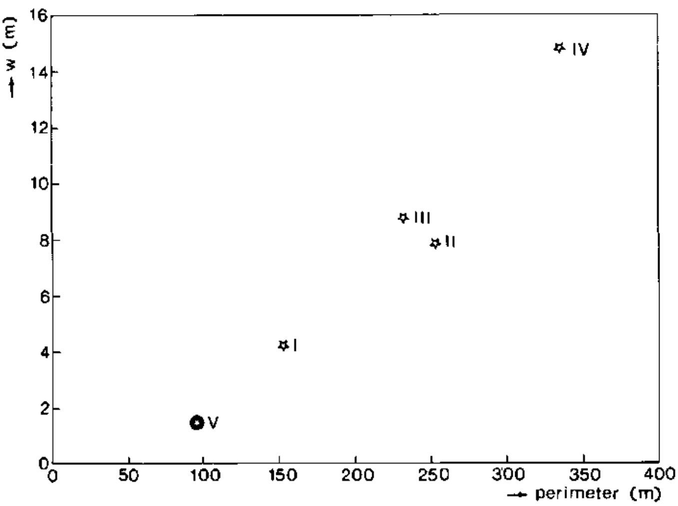

Figure 5.6 Values of w for the different greenhouses (0° < α < 10°).

The obtained values of w for the houses in fig. 5.1 are given in fig. 5.6 as a function of their perimeter. In the same figure, also the supplementary flux is inserted for the small greenhouse V (26.6 x 22.2 m^2) mentioned

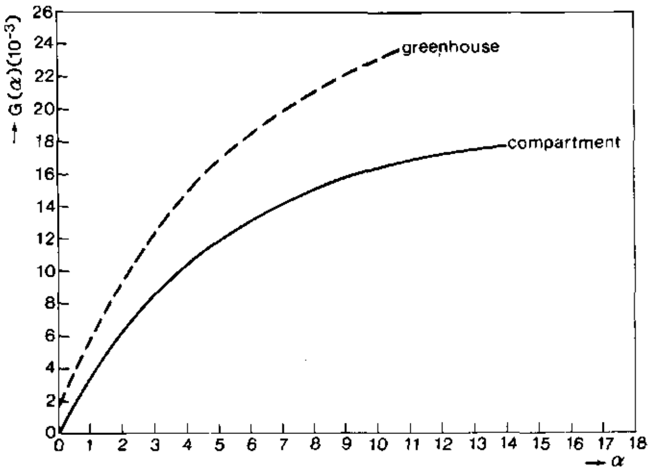

Figure 5.7 The measured ventilation functions of the 'quasi-infinite' cover (constructed compartment) and the whole greenhouse (V). Window dimension: L_o = 0.73 m, H_o = 1.55 m.

in chapter 2 (section 2.3) and chapter 3 (section 3.5). The calculation of the value w for this latter greenhouse (also for window openings up to 10 degrees) is based on the measured ventilation characteristic of the whole greenhouse (with window dimensions L_o = 0.73 m and H_o = 1.55 m) and the measured ventilation characteristic of the constructed compartment in the centre of the same greenhouse with a similar window type (eqn. 3.16, fig. 5.7). The result perfectly fits in the previously observed trend. It demonstrates once more that the effect of the additional pressures (the 'side wall effect') is relatively small for a small greenhouse.

5.4 Concluding remarks

In this chapter a pilot full scale study is presented on the ventilation properties of variously sized Venlo type greenhouses. It was for the first time that ventilation features of relatively large Venlo type greenhouse structures were determined. The measurements were performed in freestanding greenhouses with four outside walls and no partition walls. The experiments were designed to study the effect of building scale and geometry on the ventilation.

To interpret the ventilation of the greenhouses, the ventilation of the 'quasi-infinite' cover was used as a reference. It was assumed that the difference between the actual ventilation and the ventilation of the 'quasi-infinite' cover was attributed to an effect which is due to the presence of the side walls (the 'side wall effect').

The measurements show that the air exchange of the greenhouses has increased compared to that of the 'quasi-infinite' cover. The difference, the supplementary flux, is relatively small for small greenhouses while for larger greenhouses the difference is relatively large. This contradicts the expected behaviour when the 'side wall effect' is considered simply as a plain surface edge effect. It can be understood however from a qualitative consideration of the flow field over large low rise buildings, as they are described in the literature.

It appears that the ventilation characteristic of the 'quasi-infinite' cover can well serve as a reference with respect to the ventilation of large greenhouse structures. With some exploratory ventilation measurements the supplementary flux due to the 'side wall effect' can be determined. The presented graphic way to account for the supplementary flux clearly shows the relationship between this flux and the greenhouse scale. This graphic representation may be useful to indicate the 'side wall effect' for freestanding greenhouses with different surface areas.

However, a full understanding of the mechanisms that are responsible for the 'side wall effect' is not yet apparant. In this respect, a detailed full scale study of the pressure distribution and ventilation features of greenhouse A and the compartments within an identical greenhouse B (fig. 5.8) may provide valuable information. It should be remembered, however, that suitable constructions for a study adressed to the greenhouse scale and geometry on the air exchange are scarce. Variation in eaves height, leakage ventilation, window configuration and site conditions may always account for some interference and affect the results.

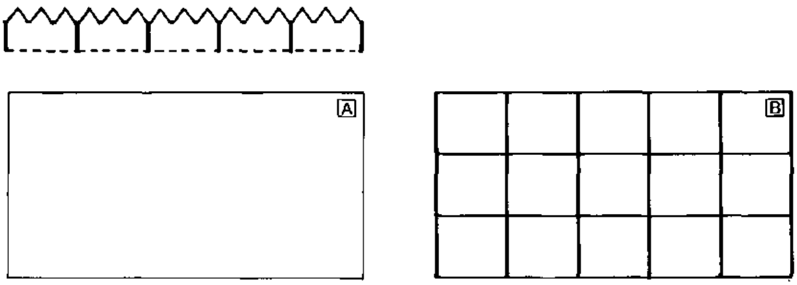

Figure 5.8 Greenhouse A (without compartments) and greenhouse B (with compartments).

5.5 References

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6 VENTILATION DUE TO THE TEMPERATURE EFFECT AND THE COMBINED WIND AND TEMPERATURE EFFECT

6.1 Introduction

Generally, when the natural ventilation in buildings is studied, a distinction is made between the air exchange caused by wind effects and the air exchange due to thermal buoyancy forces resulting from the temperature difference between the inside and outside air of the enclosure. The wind induced air exchange of Venlo type greenhouses was studied in the previous chapters. Though in practice as a rule the wind effect strongly dominates the temperature effect, the effect of thermal buoyancy on the air exchange is of fundamental interest and its importance increases when the wind is almost absent. Therefore the present chapter is devoted to the air exchange of the greenhouses due to the temperature difference between the inside and outside air, and to the air exchange due to the combined effect of wind and temperature. To really understand the temperature induced air exchange through the greenhouse window openings with its rather complex and varying geometrical configuration, basic insight is required of the natural convection through plain openings in the envelope of an enclosure. For this purpose, the natural convection was measured through rectangular openings in a horizontal and a vertical plane (section 6.2). The next section (6.3) presents an approach to estimate the temperature induced ventilation through one-side-mounted windows on a greenhouse cover together with some exploratory measurements. The results of the measurements were compared with the estimates presented earlier in this section. The aim of the work presented in section 6.2 and 6.3 is not to perform a complete study on the natural convection through the various openings, but only to offer an approach and some approximate measurements. The results are to be employed to estimate the natural convection in real situations.
In fact, the air exchange is usually due to combined wind and temperature effects. Ventilation measurements in a greenhouse, in a period with a relatively low wind speed and a high temperature difference, are discussed in section 6.4.

6.2 Natural convection through rectangular openings

Though the engineering importance of heat transfer by natural convection is widely recognized, relatively little attention is given to natural convection across openings in partitions. From extensive literature research, the present author has found only a few experimental studies in this field. Brown and Solvason [1] presented theoretical considerations for natural convection through rectangular openings in vertical partitions. Brown [2] presented a theory for openings in horizontal partitions. In both studies, the same test unit was used to measure the natural convection through mainly square openings, with varying ratios of the partition thickness to the dimension of the opening. Fritzsche and Lilienblum [3], Shaw [4] and Shaw and Whyte [5] measured the natural convection through doorways in a more practical situation.

There are a number of variables such as the area of the opening, geometry of opening and temperature difference that may be considered in any particular analysis. The shape of the opening under a one-side-mounted window varies with the opening angle. For very small opening angles, the opening area is shaped like a crack with a high aspect ratio (i.e. the geometric ratio of length (L_o) over height (H_o) of the opening). For a fully opened window, on the contrary, the aspect ratio of the opening area equals the aspect ratio of the rectangular window. The partition thickness (d) of the window opening is always very small in the case of greenhouse windows. To gain insight into the temperature induced air exchange through the windows, the natural convection through openings with varying aspect ratios and with a thickness which is small relative to the height or length, is investigated. The measurements were performed for openings in either a horizontal or vertical partition.

6.2.1 Considerations

Our study deals with natural convection in a system in which two uniform volumes of still air (for instance the inside and outside air of an enclosure) are separated by a wall with one rectangular opening. The uniform temperatures, densities and concentrations of the air are different on both sides of the wall and each of these quantities is maintained at a constant value. In our considerations we assume that the partitioning wall does not participate in any form in the transfer processes between the two volumes of air: it is impermeable to heat and mass transfer and it cannot take up or dissipate mass or energy. The occurring heat flow through the opening is then only due to the differences in air conditions and is not influenced by any temperature effect of the wall. The opening area A in the wall is considered to be small compared to the dimensions of the wall.

The conditions formulated in the foregoing paragraph seem somewhat unrealistic, but they are inevitable when we want to study the pure effect of natural convection by temperature difference between two portions of air only.

Vertical openings

In fig. 6.1 the system under consideration is shown. For this situation, according to the theory presented by Brown and Solvason [1], the air interchange across the opening is driven by the variation of the hydrostatic pressure on both sides of the opening. A neutral pressure plane was defined as the height (h_o) at which the thermally induced pressure difference is zero:

$$p_1(h_o) = p_2(h_o) = p_o \tag{6.1}$$

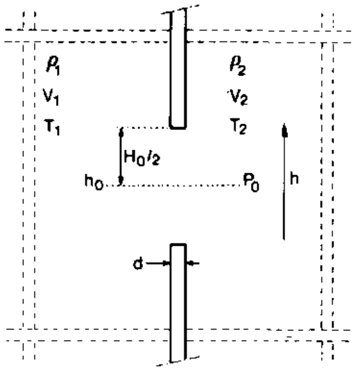


Fig. 6.1 Schematic representation of natural convection through an opening in a vertical partition.

The hydrostatic pressures on each side of the opening at height h are given by:

$$p_1(h) = p_o - \rho_1 \cdot g \cdot (h_o - h) \qquad (6.2)$$

$$p_2(h) = p_o - \rho_2 \cdot g \cdot (h_o - h) \qquad (6.3)$$

with g the gravitational acceleration and ρ_1 and ρ_2 the densities of the air in the two compartments. It is to be noticed that g is negative when h is positive in upward vertical direction. The pressure difference between the two sides at the same height h is thus:

$$p_1(h) - p_2(h) = (\rho_2 - \rho_1) \cdot g \cdot (h_o - h) = \Delta\rho \cdot g \cdot (h_o - h) \qquad (6.4)$$

We notice that for $\rho_1 > \rho_2$ the flow direction below the reference level ($h < h_o$) is from volume 1 to volume 2. Above reference level the flow direction is reversed. Since both volumes are sealed, we may assume that there is no net volume flow across the opening. According to symmetry considerations the position of the neutral plane is in the centre of the opening. When more openings are vertically separated in the building envelope, the level at which the transition between inflow and outflow occurs, the neutral pressure plane, is determined such that a flow balance is maintained (i.e. the total flow across the openings above the neutral plane is equal but opposite in direction to that below that plane).
If only a temperature difference accounts for the difference in density between the air in both volumes, we can write:

$$-(\rho_1 - \rho_2) = \rho \cdot \beta \cdot (T_1 - T_2) \qquad (6.5)$$

with T_1 and T_2 the temperatures in volume 1 and 2 respectively and β the thermal expansion coefficient. For frictionless flow through the opening, the Bernoulli equation holds. We can therefore write, using eqn. 6.4:

$$\Delta\rho \cdot g \cdot (h_o - h) = \frac{1}{2} \cdot \rho \cdot v^2 \qquad (6.6)$$

Thus, combining eqn. 6.6 and 6.5:

$$v = \left[|2 \cdot g \cdot \beta \cdot \Delta T|\right]^{\frac{1}{2}} \cdot \left[|h_o - h|\right]^{\frac{1}{2}} \qquad (6.7)$$

where v is the air velocity and $|h_o - h|$ and $|2 \cdot g \cdot \beta \cdot \Delta T|$ are the absolute

value of (h_o-h) and $(2 \cdot g \cdot \beta \cdot \Delta T)$ respectively. The direction of the velocity at height h is determined by the sign of the term (h_o-h).
The air exchange rate Φ_V through the upper part of the opening can subsequenly be found by integration of eqn. 6.7 from the reference height $h = h_o$ to $h = h_o + H_o/2$.

$$\Phi_v = \int_{h_o}^{h_o + H_o/2} \left[|2 \cdot g \cdot \beta \cdot \Delta T|\right]^{\frac{1}{2}} \cdot L_o \cdot \left[h-h_o\right]^{\frac{1}{2}} \cdot dh \tag{6.8}$$

so that

$$\Phi_v = L_o/3 \cdot \left[|g \cdot \beta \cdot \Delta T|\right]^{\frac{1}{2}} \cdot \left[H_o\right]^{3/2} \tag{6.9}$$

In many procedures, a discharge coefficient C is introduced into eqn. 6.9 to account for the energy losses in the opening:

$$\Phi_v = C \cdot L_o/3 \cdot \left[|g \cdot \beta \cdot \Delta T|\right]^{\frac{1}{2}} \cdot \left[H_o\right]^{3/2} \tag{6.10}$$

The energy dissipation of the flow through rectangular openings in case of forced convection was expressed as a friction factor F_o, which was mainly determined by the aspect ratio of the opening (chapter 2 of the present thesis). This was represented in an Euler-like relationship:

$$\Delta P \ / \ \left[\frac{1}{2} \cdot \rho_o \cdot v^2\right] = F_o(L_o/H_o) \tag{6.11}$$

with v the average velocity in the opening. Though the flow conditions for the forced and natural convection are not identical, application of the friction factor F_o in the considerations of natural convection may be relevant since F_o represents a total discharge and takes into account the effect of the geometry of the rectangular openings. Equation 6.9 then becomes:

$$\Phi_v = L_o/3 \cdot \left[|g \cdot \beta \cdot \Delta T|/F_o\right]^{\frac{1}{2}} \cdot \left[H_o\right]^{3/2} \tag{6.12}$$

or, looking at eqn. 6.10

$$C = F_o^{-\frac{1}{2}} \tag{6.13}$$

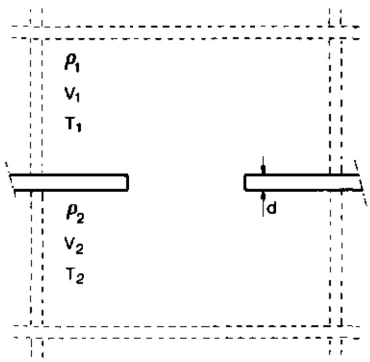


Fig. 6.2 Schematic representation of natural convection through an opening in a horizontal partition.

Horizontal openings

Figure 6.2 gives a schematic representation of the situation where natural convection takes place through an opening in a horizontal partition. Two sealed volumes, containing fluid at densities ρ_1 and ρ_2 respectively are separated by a horizontal partition of thickness d and having one opening. In principle, the two layers of air at rest are in equilibrium, even when the heavier air overlies the lighter. However, when the cold air moves downwards and the hot air upwards, there is a release of potential energy, which can provide kinetic energy for the motion. Thus the equilibrium will be unstable and exchange will take place of the lighter against the heavier air. However, a general description of the flow in this situation is rather complicated due to the unstable flow conditions at the opening. In contrast to the natural convection through vertical openings, no steady pressures and flow distribution can be assumed. Brown presented a theory applying the Bernoulli equation for the fluid flowing through the opening. In his considerations, the thickness d of the partition was essential to define the pressure gradient $\rho \cdot g \cdot d$ in the Bernoulli equation. In our case, this theoretical approach does not seem workable since the partition thickness of the openings in the experiments is too small to define a significant pressure difference. A detailed theory, dealing with this unstable and complicated system, is not available. Looking at comparable situations where natural convection takes place between compartments with different temperatures, we expect an interchanging flow of rising and falling eddies through the horizontal opening (or part of that opening). The exchanged volumetric flux is expected to be dependent on the temperature difference of the air across the opening and the geometric characteristics of the opening. This will be examined in the measurements reported in the next sections of the present chapter.

6.2.2 Experimental procedure

In reality, when natural convection through an opening in a wall of a building is considered, the temperature effect arises as a result of difference in temperature and hence air density between the inside and outside of the building. Though in this case we are, strictly speaking, not dealing with two sealed volumes at different air conditions, we may assume that in principle the same theoretical considerations can be applied and that the air exchange is caused by the imbalance in the pressure gradients of the air on both sides of the opening.

In our experiments, a temperature difference was created between the inside and outside of a cubical enclosure (l = b = h = 2.5 m) with an opening in either the horizontal or vertical wall of the enclosure (fig. 6.3). Two types of openings were applied in the experiments, both with the same surface area but with different length/height ratio (17 x 17 cm; L_o/H_o = 1, and 120 x 2.4 cm; L_o/H_o = 50). The thickness (d) of the openings equaled 3 mm. The inside of the cube was sealed up in a gastight way with aluminium foil. Tests were carried out with temperature differences across the opening ranging from about 1 to 25 degrees centigrade, as this is the region occuring in actual practice. To generate the temperature difference between the interior and the exterior air, the enclosure contained a convector with a large heat exchange area. Clearly the presence of the convector contradicts the supposition of still air in the cube. However, our experiments will clarify that the influence of this effect can be eliminated. The heating system was controlled to maintain a constant (adjustable) air temperature in the cube. The effective

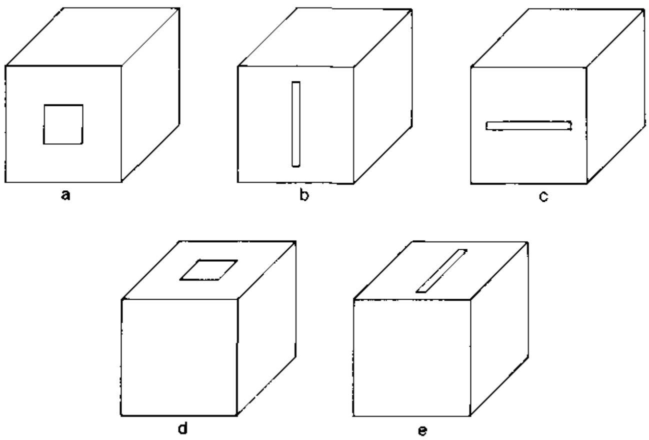


Fig. 6.3 Cubical enclosure with opening in horizontal or vertical wall (not on scale).

ventilation flux through the opening, due to the temperature difference, was measured by means of the tracer gas decay rate method.
When equilibrium conditions were reached, the tracer (N_2O) was carefully distributed in the cube by means of a perforated tube on ground level. After release of the tracer, the perforated tube in the enclosure containing the N_2O, was flushed out cautiously by N_2 gas to stimulate the initial mixing of the tracer gas and the inside air and to prevent a disturbance of the measurements due to diffusion of tracer from the tube. To measure the N_2O concentration during the experiments, the air was sampled at different points in the enclosure and led to an IR analyser through a small pump. Inside the enclosure, four very thin thermocouples were arranged to measure the air temperature at various locations. The temperature sensor outside consisted of a psychrometer (platinum resistance thermometer) located a few meters from the opening. During the measurements, the concentration of tracer gas and the temperatures inside and outside the enclosure were monitored at certain intervals.
The test area was situated in a large hall of the Institute of Agricultural Engineering (IMAG) in Wageningen. To eliminate effects of local air movements, the set up was completely shielded by a screen of blister-

padding with dimensions 10 x 10 x 6 m (l x w x h). Moreover, the measurements were performed during the evening and night, when all the doors in the hall were kept closed.

6.2.3 Results and discussion

The results of the measurements are given in fig. 6.4 and 6.5 for vertical and horizontal openings respectively. In these figures, the measured effective air transfer to the environment, Φ_V, is ordinate and the square root of the temperature difference is abscissa.

For the vertical openings (fig. 6.4), the measured linear relationship between Φ_V and $(\Delta T)^{\frac{1}{2}}$ is in agreement with the theory (eqn. 6.10). The slope of the lines through the experimental results increases for the openings with smaller aspect ratio as was indicated by eqn. 6.9. When the experimental results for the vertical openings are evaluated, applying eqn. 6.10, the discharge coefficient C for the different apertures can be found (see table 6.1).

Table 6.1 The measured discharge coefficients for the vertical openings under study.

aspect ratio L/H	measured discharge coefficient C	calculated $F_o^{-\frac{1}{2}}$
1	C_1 = 0.60	0.64
1/50	C_2 = 0.60	0.69
50	C_3 = 0.74	0.75

The values in table 6.1 are in line with findings in previous research. Brown and Solvason found discharge coefficients between 0.6 and 1.00 for the different openings in the range $10^7 < Gr < 10^8$ and $0.19 < d/H_O < 0.38$. Our experiments encompass a range of the Grashof number from 10^3 to 10^9 and a range of the ratio of partition thickness to opening height of 0.125-0.0025. Shaw found for large rectangular door openings discharge

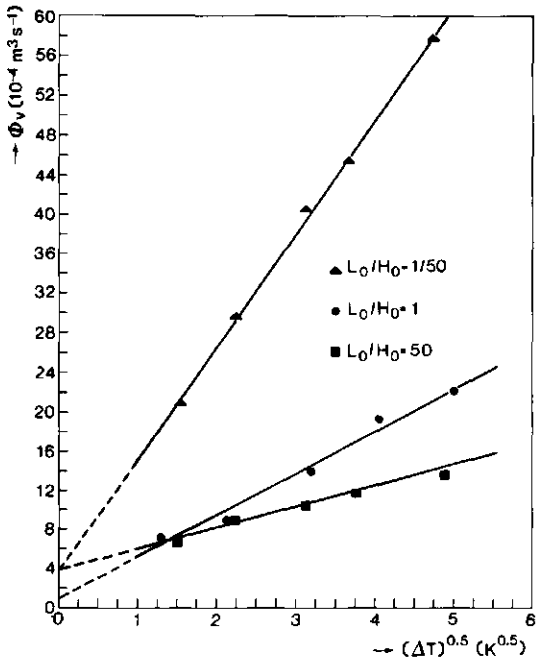


Figure 6.4 Measured natural convection through the vertical openings.

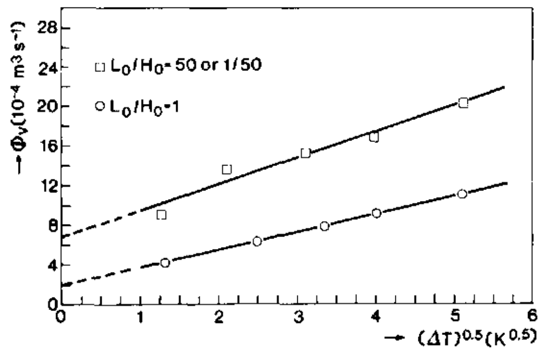


Figure 6.5 Measured natural convection through the horizontal openings.

coefficients $C \approx 0.8$ for temperature differences between 4°C and 10°C, the door geometry not being significant.

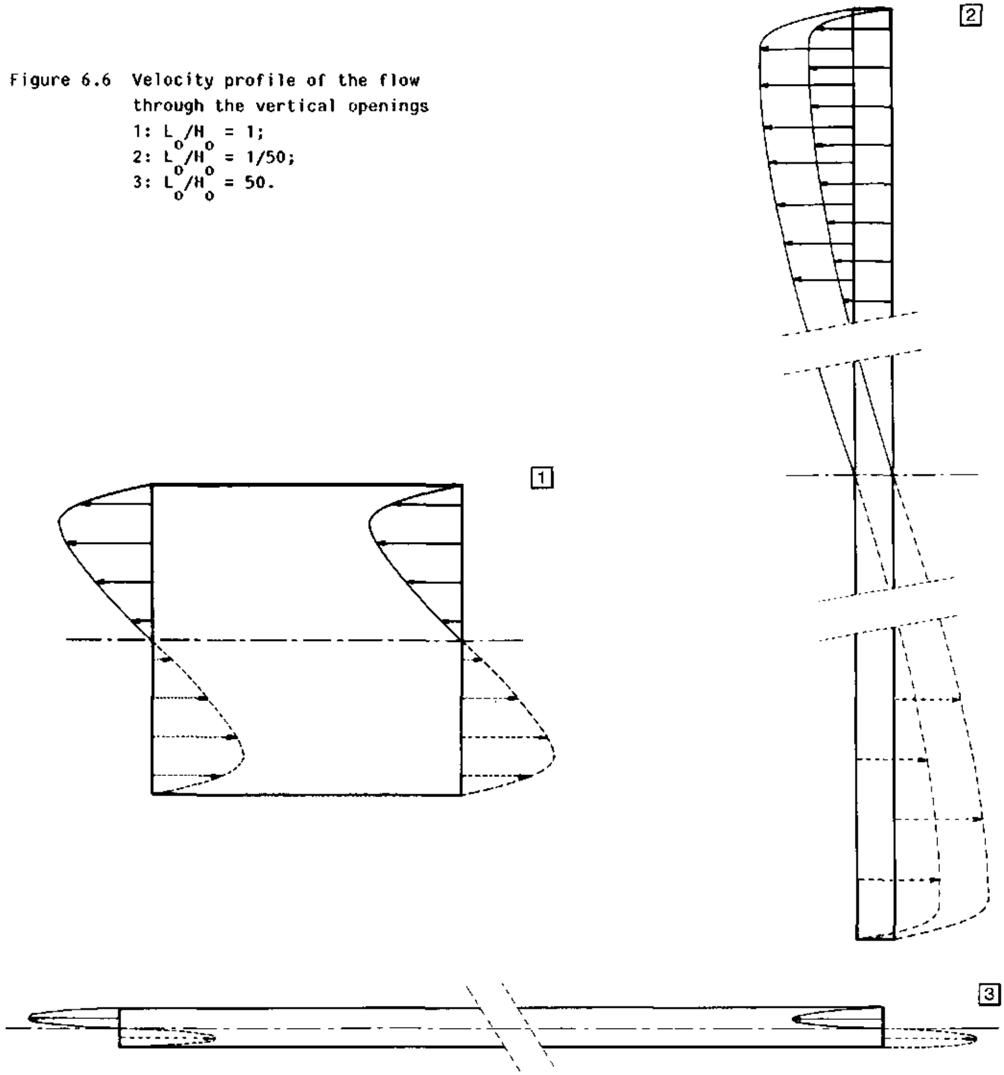
The present experimental results indicate that the discharge coefficients vary for the rectangular openings under study. A similar effect was observed in chapter 2 of the present thesis, when the flow through the same kind of openings, generated by a uniform pressure difference across the opening, was discussed. For the forced convection, the friction factor F_o of the opening was a function of the aspect ratio of the opening, being symmetrical with respect to $L_o/H_o = 1$ (eqn. 2.2a and 2.2b). For natural convection, however, it appears that the discharge coefficient for the opening with aspect ratio 1/50 and 50 are different. Evidently, the discharge in the opening is also determined by the pressure and flow field in the opening.

Fig. 6.6 shows the velocity profile of the flows across the different rectangular openings for the same volume flow rates. For the opening with aspect ratio 1, it is possible that the air streamline converges at both sides within the opening. The different velocity distribution in the openings for the aspect ratios 1/50 and 50 indicate that a one-dimensional contraction of the air may occur within the opening with aspect ratio 50, while a two dimensional contraction of the air flow is more likely within the opening with aspect ratio 1/50.

In this connection it is interesting to compare the measured values of C_1, C_2 and C_3 and the calculated values of $F_o^{-\frac{1}{2}}$ according to eqn. 6.13 in table 6.1 (realizing that the aspect ratios used for the inflow and outflow are 2, 1/25 and 100 for the openings with aspect ratio 1, 1/50 and 50 respectively).

For the openings with aspect ratio 1 and 50 the agreement between the theoretical value $F_o^{-\frac{1}{2}}$ and the measured discharge coefficient is good, while for the opening with aspect ratio 1/50 a greater uncertainty exists. It appears that the difference between the calculated discharge values, based on a uniform pressure and flow field, and the measured discharge values for natural convection is more pronounced for the openings with small aspect ratios. The fact that the flow regime for natural convection is strongly associated with the height H_o might be an explanation for this trend. Though indications for a dependency on the aspect ratio are found, a quantitative relationship between the discharge coefficients for natural

Figure 6.6 Velocity profile of the flow through the vertical openings
1: $L_o/H_o = 1$;
2: $L_o/H_o = 1/50$;
3: $L_o/H_o = 50$.



convection and the dimensions of the openings is not, at present, apparant. More accurate figures can be generated when the air transfer is measured through a larger number of openings with varying aspect ratios. As yet, for practical purposes, a value of C = 0.6 seems to be a reliable estimate of the discharge coefficients for a vertical sharp edged opening in case of natural convection.

The test results for natural convection across the horizontal openings (fig. 6.5), also show a linear relationship between Φ_v and $(\Delta T)^{\frac{1}{2}}$, for temperature differences ranging from about 1-25 degrees centigrade. From the experiments on the natural convection through horizontal openings, no conclusions can be drawn about the structure of the convection, in particular regarding the sequence of rising and falling cells. The flow may be steady in a fairly regular pattern, or convection cells may occur with great variability in size and shape. It was expected that the combined action of the rising and falling fluid was sensitive to the geometric characteristics of the opening. This seems to be corroborated by the experimental results where the slope of the Φ_V versus $(\Delta T)^{\frac{1}{2}}$ relation depends on the geometry. For the square opening, the fluid may fall and rise in different quadrants of the opening. In this case, the shape and size of the convection cells are not necessarily determined by the length or width of the opening. For an opening with a large aspect ratio and shaped like a split, the bouyant plume width may be mainly determined by the length of the shortest side.

The figures 6.4 and 6.5 show an extrapolated transfer volume at zero temperature difference. This transfer is probably caused by the fact that the air inside and outside the cube is not completely at rest, even when $\Delta T = 0$. This turbulence of the adjoining spaces makes it impossible to completely prevent transfer. From the ventilation fluxes at $\Delta T = 0$ (by extrapolation), it appears that the turbulence inside and outside the cube has only small influence on the transfer through the openings.

6.3 Natural convection through the greenhouse windows

6.3.1 Considerations

In fig. 6.7, two different greenhouse windows at different opening angles are pictured. From the experiments in the previous section, it can be concluded that the main driving force for the ventilation due to natural convection is related to the height of the opening (i.e. the vertical pressure gradients of the inside and outside air masses).
Analogous to the theoretical considerations in section 6.2.1, we may assume that a difference in pressure between the inside and outside of the

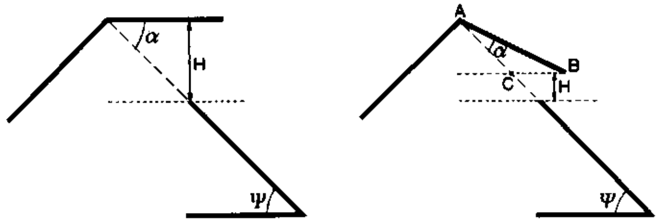


Figure 6.7 Greenhouse windows at different opening angles.

greenhouse window occurs at all points above and below the neutral pressure plane as a result of differences in air density between the interior and exterior. The pressure difference varies directly with the distance from the neutral pressure plane. Natural convection will occur through the side areas and front area of the window opening. From fig. 6.7 it can be seen that the height of the side area is relatively large at a small window opening angle. Consequently it can be expected that the side areas have their effect, especially for small opening angles. For a thorough discussion on the ventilation through the different areas, the reader is referred to the thesis of Bot [6]. According to his considerations for a window with aspect ratio equal to 1, the importance of the flux through the side areas decreases very quickly for larger openings. Therefore it should only be considered for opening angles smaller than 10 degrees. For windows with a higher aspect ratio, the effect of the side areas becomes even smaller.

In practice, the influence of temperature induced ventilation in the greenhouse is more important during summer conditions when the windows are widely opened. Then the natural convection mainly occurs through the front area of the window opening. For the roof window opening, the height H (fig. 6.7) equals:

$$H = H_o \cdot [\sin\Psi - \sin(\Psi - \alpha)] \qquad (6.14)$$

An expression for the temperature induced ventilation through the front area of the window with height H and length L_o can be found according to eqn. 6.10:

$$\Phi_v = C_f \cdot L_o/3 \cdot \Big[|g \cdot \beta \cdot \Delta T|\Big]^{\frac{1}{2}} \cdot \Big[H\Big]^{3/2} \qquad (6.15)$$

with:

C_f = discharge coefficient for the flux through the front area

To investigate whether this expression gives a reliable estimation of the temperature induced air exchange through the windows, some ventilation measurements were carried out on a model greenhouse.

6.3.2 Experimental set up

Basically the ventilation through a one-side-mounted window was measured with a similar experiment as described in section 6.2.2. The ventilation measurements were carried out with a model greenhouse (fig. 6.8), which was located in a room with dimensions 7 x 5 x 4 m (l x w x h). The model greenhouse was well sealed to prevent any leakage. Both the room and the greenhouse were heated by a convector. The temperatures inside the room and in the greenhouse were measured by means of a platinum resistance thermometer and were controlled to maintain a desired temperature difference between the inside and outside of the greenhouse. Measurements were performed at various temperature differences and at relatively large window opening angles of α = 16.7°, 32° and 50°. The relatively small volume of the greenhouse may increase the sensitivity of the system to disturbances of the environmental conditions. To extend the measuring time and so to increase the reliability of the measurements, the temperature differences were chosen to be relatively small. During the measurements

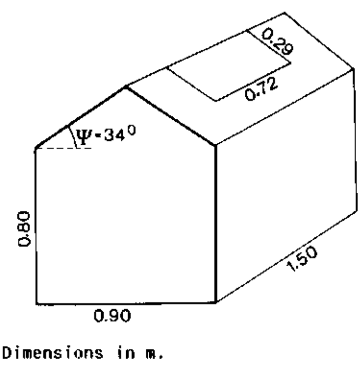


Figure 6.8 Model greenhouse. Dimensions in m.

the doors and the windows of the room were kept closed to prevent undesired air circulation.

6.3.3 Results and discussion

In table 6.2, the measured ventilation and estimated ventilation according to eqn. 6.15 (with C_f = 0.60, see section 6.2.3) are given for various temperature differences between the inside and outside of the model greenhouse. In the table, for sake of comparison, the ventilation is expressed as ventilation rate R, i.e. the number of complete air changes per hour.

Table 6.2 The measured and calculated ventilation due to temperature effects for different window opening angles and temperature differences.

α	ΔT	R calculated (h^{-1})	R measured (h^{-1})
16.7	3.6	2.9	3.2
	9.1	4.6	5.0
32.0	3.8	8.3	9.0
	16.4	17.3	15.2
50.0	3.8	9.2	10.9

Though the number of experiments is limited and the experimental accuracy is restricted, the figures in table 6.2 clearly indicate that agreement between the experimental results and the predicted ventilation is fairly good. The derived expression in eqn. 6.15 therefore allows a calculation of the magnitude of the temperature induced ventilation, which can be used for practical purposes.

6.4 Air exchange due to a combined wind and temperature effect

6.4.1 Considerations

In reality pure natural convection will seldom be met. As a rule the effects of wind and temperature driven ventilation will occur simultaneously. The respective pressure components (i.e. the fluctuating pressures due to the wind and the static pressures due to the temperature difference) can be superimposed to obtain the total pressure at each window opening:

$$\Delta P_{combined} = \Delta P_{wind} + \Delta P_{temp} \tag{6.16}$$

Here we also apply a vector summation of wind and temperature driven ventilation, in the same way as succesfully applied in the literature for simultaneous free and forced convection on solid bodies (Börner [7]). In our case this vector summation of the respective volume fluxes leads to:

$$\Phi_{v\ combined} = (\Phi^2_{v\ wind} + \Phi^2_{v\ temp})^{\frac{1}{2}} \tag{6.17}$$

The measured total greenhouse ventilation caused by thermal buoyancy and wind forces can be evaluated when the magnitude of the air exchange components due to the wind and temperature effects can be estimated separately. The wind induced ventilation can be calculated when the ventilation characteristic of the greenhouse cover, expressed by the ventilation function $G(\alpha)$, is known.

Since all windows on the greenhouse cover are located at the same height, we may assume that there is no temperature induced vertical pressure difference between the different window openings. As a result, each window opening should be considered individually. Equation 6.15 with ($C_f = 0.6$) can be used to estimate the air exchange through the window openings due to temperature effects.

In the next sections ventilation measurements are discussed, which were carried out in a compartment during periods with relatively low wind speeds and large temperature differences. In this situation both the temperature and wind effects substantially contribute to the total ventilation.

6.4.2 Experiments

In the constructed compartments IV and V mentioned in chapter 3, the heating system was switched on during a period with calm wind. During this period, with a relatively low wind speed and large temperature difference

between the interior and exterior of the compartment, ventilation measurements were performed for some large window opening angles.
The measured total ventilation in the compartments was compared with the combined ventilation flux ($\Phi_{v\ combined}$), calculated from the separately estimated ventilation components according to eqn. 6.17. The term $\Phi_{v\ wind}$ in eqn. 6.17 was calculated from the ventilation function $G(\alpha)$ according to eqn. 3.11 in chapter 3. This function characterizes the wind induced air exchange through windows with dimensions L_o = 1.46 m and H_o = 0.80 m, equipped on a 'quasi-infinite' cover. The term $\Phi_{v\ temp}$ was estimated according to eqn. 6.15 with C_f = 0.6. The temperature difference which was used in the analysis of the results was that of the recorded average temperature difference between the inside and outside air during the measuring run.

6.4.3 Results and discussion

In table 6.3, the measured total ventilation at various window opening angles, the estimated terms $\Phi_{v\ wind}$, $\Phi_{v\ temp}$ and $\Phi_{v\ combined}$ and the recorded environmental conditions are collected.
From the values in table 6.3 it can be noted that agreement between the estimated and measured total ventilation is fairly good. The measurements presented here show a maximum error between the predicted and measured ventilation of around 20%. Obviously, a full understanding of what factors

Table 6.3 The measured and predicted ventilation due to the combined action of wind and temperature.

opening angle α	average wind-speed $\bar{u}$	temperature difference ΔT	$\Phi_{v\ wind}$ (10^{-3})	$\Phi_{v\ temp}$ (10^{-3})	$\Phi_{v\ comb}$ (10^{-3})	$\Phi_{v\ measured}$ (10^{-3})
42.0	2.15	15.7	49.58	43.43	65.91	82.29
42.0	3.35	16.2	77.49	44.11	89.16	94.88
25.1	2.98	15.2	55.44	40.58	68.70	75.96
25.1	2.93	14.8	54.57	40.04	67.68	81.54
11.2	3.31	14.9	36.53	11.47	38.31	45.91
11.2	2.30	16.8	25.45	12.18	28.21	33.00

may be responsible for the apparent differences, requires a more extended test program. The results, however, indicate that the measuring procedure and considerations presented in this section can be useful in estimating the combined effect of wind and temperature on the ventilation.

6.5 Concluding remarks

Measurements on the natural convection through horizontal and vertical rectangular openings showed that the discharge for the flow is affected by the geometrical characteristics of the opening. For vertical openings the measurements indicate that the actual discharge is also determined by the pressure and velocity distribution in the opening. The difference between the vertical outside and inside pressure gradients across the openings can be considered as the main driving force for the ventilation.
On the basis of the experimental results, an approach was presented to describe the natural convection through the one-side-mounted windows on the greenhouse cover (section 6.3). Ventilation experiments conducted on a model greenhouse lend support to the given approach.
So far, the effects of wind and temperature on the ventilation have been considered separately. In section 6.4 ventilation measurements were presented in a compartment during periods in which both the temperature and wind effects contributed simultaneously to the total ventilation. Though the separate effects on the ventilation are fairly well understood, the estimation of the combined effect was somewhat too low. The results however, indicated that the relationships presented can be used as a rule of thumb to estimate the combined effect of wind and temperature. To understand the combined action of wind and temperature in detail, more research has to be done. The considerations presented in this chapter provide a good starting point for future research.

6.6 References

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7 FINAL DISCUSSION AND CONCLUSIONS

The ventilation of greenhouses can be provided mechanically by fans or by natural ventilation. In most cases, the air exchange of greenhouses takes place by natural ventilation systems. In the present thesis, the natural ventilation of multi-span greenhouses is investigated. A thorough knowledge of the ventilation is important with respect to the climate management of the greenhouses (chapter 1).
Two natural origins can be held responsible for the natural ventilation, namely the wind around the greenhouse and the buoyancy of the warmer air in the greenhouse. It can be concluded that the temperature-driven ventilation appears mainly of importance under still conditions. However, the temperature effect could be quantified in a satisfactory way (chapter 6). In chapter 6 thereupon the combined effect of wind and temperature on the air exchange were studied. The findings of the measurements show that the combined effect of wind and temperature on the ventilation can be calculated as a linear superposition of the separate effects. As mentioned before, in most circumstances the wind effects amply dominate the temperature effects. The present thesis is therefore mainly adressed to the wind induced air exchange of the multi-span greenhouses.

As a starting point for the description of the greenhouse ventilation due to wind effects, the ventilation through a 'quasi-infinite' cover was considered. The 'quasi-infinite' cover is defined in this thesis as a greenhouse cover where the wind field near the surface is not influenced by any boundary effect. Starting from this model the effects of the wind and various greenhouse parameters on the ventilation can be studied. The concept of the 'quasi-infinite' cover was also introduced to serve as a reference for the ventilation of the real greenhouses. For the 'quasi-infinite' covers it was assumed that all windows were operating under the same conditions and that there was no effect of the side walls (the finiteness) of the cover on the air exchange. An approach to describe the ventilation through these windows in this 'quasi-infinite' cover was already outlined in a prior study by Bot (1983). Measurements, however, were carried out in a small compartment only. A major goal in the present investigation was to thoroughly evaluate the existing description of the ventilation process through window openings in a more general 'quasi-infinite' greenhouse cover. The full scale determination of the flow characteristics of the windows (chapter 2) formed a substantial part of this evaluation.

In the given description, the ventilation through the windows on a 'quasi-infinite' cover is characterized by the ventilation function $G(\alpha)$. This function relates the ventilation flux through the windows (per unit window area) to the average wind speed at reference level, in dependence of the opening angle. From a physicists point of view the function $G(\alpha)$ can be considered as a transform coefficient: it translates the average windspeed at reference level to the time-averaged superficial windspeed in one half of the window openings (through one half the flux is in, through the other half the flux is out).
On the basis of our performed experiments (chapters 2,3 and 4) it was concluded that the given description provides a good representation of the air exchange. The results of our experiments confirm our presumption that the window dimensions play a double role in the ventilation process: they determine the resistance for the flow through the windows (chapter 2) and they affect the effectivity of the pressure fluctuations in relation to the wind speed at reference level (chapters 3 and 4). The assumption that, for a 'quasi-infinite' cover, a similar averaged ventilation behaviour exists for each window was firmly established by our experiments. The total flux through the cover can be calculated on the basis of the empirically determined ventilation function $G(\alpha)$ and the number of windows on the cover (calculated from the surface area of the cover and the window to cover ratio A_0/A). The effect of the whole cover is found as a superposition of the effects of the single windows.

Ventilation measurements in freestanding greenhouses with different geometries and surface areas showed an increase of the ventilation compared to that of the 'quasi-infinite' cover (chapter 5). In our approach to interpret the ventilation of the greenhouses, we assumed the effect of the finiteness (the 'side wall effect') to be superimposed on the ventilation flux due to the pressure fluctuations only (i.e. the ventilation through the greenhouse cover as if it were a 'quasi-infinite' cover). Surprisingly, this 'side wall effect' appeared to be larger for the greenhouses with a large surface area. Superposition of the 'side wall effect' to the general 'infinite cover' approach may lead, however, to an acceptable description of the ventilation in these freestanding greenhouses.

Looking at the complete results of our research we may conclude that the concept of the 'quasi-infinite' cover is a sound basis for the description of the greenhouse ventilation. The investigations in chapters 2, 3 and 4 therefore certainly provide valuable support. A quantitatively reliable description of the air exchange of all multi-span greenhouses can be derived, starting from this concept.
Another conclusion from our research is that the linear superposition of separate effects leads to an acceptable picture of the combined ventilation. This holds true for the combined effects of several windows, for the combined effects of leeside and windward side ventilation and for the combined effect of wind-driven and temperature-driven ventilation. This superposition principle is probably also applicable for freestanding greenhouses where the 'side wall effect' is to be added to the 'infinite cover effect'. The 'side wall effect' of any greenhouse, which is dependent on both the greenhouse dimensions and site conditions and therefore different for each greenhouse, can now easily be determined by some investigatory measurements.

The tracer gas method, used in our experiments to infer the ventilation rates, assumes a perfect mixing of the air in the greenhouse. A comparison of the results from a equilibrium concentration method (Bot) and the rate of decay method (chapter 3) indicates that the whole physical volume of the greenhouse participates in the air exchange. The same conclusion can be drawn from an additional experiment which we performed in the compartment, determining the decay rates at several points during the same measuring run. It was found that the different parts in the compartment loose tracer at the same rates. Apparantly there are no significant

stagnant pockets of air in the compartment. Since the greenhouse can be considered as a chain of similar compartments, it is plausible to assume that the mixing of the air in the greenhouse is comparable to that of the air in the compartments and that the decay method is also appropriate to estimate the ventilation rates in large greenhouse structures.
However, since the mixing of the air is never perfect, measurements made at one point in the greenhouse may not be reliable. To offset this, the air was sampled at several locations and mixed before the concentration of tracer in the air was measured.

In our investigation, empty (single enclosed) greenhouse structures were considered in which the mixing of air can be assumed to be rather effective. The mixing process of the air in a greenhouse in operation, however, may be considerably influenced by the presence of a crop or by the application of thermal screens. It is suggested to direct further investigations primarily on the effect of the crop and the screens on the intraspace mixing and consequently on the effective ventilation in the greenhouses at crop level.

SUMMARY

The objective and frame work of the present thesis is explained in chapter 1. It was stated that more insight into the air exchange mechanism of naturally ventilated buildings is important to improve the climate control of the buildings. This research was directed towards the ventilation of large multi-span greenhouses. Numerical parameters were collected for the Venlo type greenhouses. The prior study by Bot (1983) on the ventilation of the Venlo type greenhouse served as a starting point for our research. In Bot's work, a general description of the greenhouse ventilation was outlined. Many parameters, however, were determined in model studies. Ventilation measurements were performed in one small greenhouse compartment only. The aim of the present work was to contribute to a quantitative description of the air exchange of any large Venlo type greenhouse. This requires the full scale determination and evaluation of the relevant parameters which play a role in the ventilation process.

In general, the ventilation of a building is determined by the pressure distribution around the building and the geometry and location of the (window-) openings. The pressure differences across the openings act as the driving force for the air exchange. These pressure differences are caused by wind as well as by temperature effects. The air flux through the window openings is also determined by the flow characteristics of the openings, which relate the volume flux through the opening to the existing pressure difference across the opening. The flow characteristics of the greenhouse windows vary with the geometry and opening angle. Obviously, the flow characteristic of the window is a vital element in the description and understanding of the air exchange.

The windows of the modern multi-span greenhouses are all located on the cover in a regular pattern. The window dimensions may vary for the different greenhouses. For one particular greenhouse, however, the dimensions of all windows are usually the same. The first object of our research was to perform in situ measurements for the validation of an approach which a

priori describes the flow characteristics of the greenhouse windows (chapter 2). The results of the performed full scale measurements were in agreement with the previously performed measurements by Bot on scale models. Measurements were carried out for different window types and opening angles for both flow directions (inflow and outflow). The results definitely confirmed the presented approach which now can be recommended for a sound description of the air exchange of greenhouses in practice.

Though in practical circumstances the wind effects are dominant, the ventilation due to the temperature difference between the inside and outside air is of fundamental interest. The temperature effect on the ventilation through the greenhouse windows is studied in chapter 6. This temperature-driven ventilation was measured through openings with very different aspect ratios in a horizontal as well as in a vertical plane. On the basis of the results, an expression was derived to estimate the ventilation flux through the window openings caused by temperature effects. The results of experiments on a model greenhouse supported the presented approach. Next, an expression for the combined effect of temperature and wind on the air exchange was given. Full scale measurements showed that this expression provides a good representation for practical purposes.

In chapters 3, 4 and 5 the effect of the wind on the ventilation through the windows was studied. The research focussed mainly on the leeside ventilation because this type of ventilation can be regarded as the most important type of ventilation in horticultural practice.
As a point of departure in our description of the ventilation through the whole cover, the ventilation features of the so-called 'quasi-infinite' greenhouse covers (i.e. covers of fully enclosed greenhouse compartments, located relatively far from the outside walls) were considered. For this type of cover, it is assumed that the time averaged pressure distribution around each window on the cover is identical and that there is no effect on the ventilation of the additional pressures near the outside walls. It behaves as it were a greenhouse cover without side walls.
A description of the ventilation process in this situation, which makes allowances for turbulent fluctuations is presented in chapter 3. In this description the ventilation through the windows on the cover is expressed

by a ventilation function $G(\alpha)$ which describes the relation between the ventilation flux per unit window area of the cover surface and the average wind speed, in dependence of the opening angle of the windows. The measurements on the ventilation through the greenhouse windows operating under comparable circumstances (i.e. mounted on a 'quasi-infinite' cover) provided valuable insight in the ventilation process. The effects of wind speed, wind direction and window dimensions were investigated.

The description outlined above was well confirmed by the results of the measurements. A linear relationship has been demonstrated between the air flux and the average windspeed at reference level for leeside and windward side ventilation (chapters 3 and 4). Leeside and windward side ventilation functions $G(\alpha)$ are measured for windows with different dimensions mounted on a 'quasi-infinite' cover (chapters 3 and 4). The ventilation features vary for the windows under study. For a window with a small aspect ratio the initial increase of the ventilation is faster than that for a window with a large aspect ratio. The differences can partly be explained by the flow characteristics of the windows. From the measurements, however, it is also concluded that the pressure fluctuation coefficient $K_f(\alpha)$ is affected by the window type and the opening angle. This suggests that the window dimensions and opening angle play a double role in the ventilation process: they determine the flow characateristics of the opening and affect the translation of the kinetic energy of the wind field to the pressure fluctuations near the window opening. This also implies that the ventilation functions of various windows can not be predicted a priori even when the flow characteristics of the windows are known. For this, more insight into how the pressure fluctuation coefficient is related to the window dimensions and opening angle is necessary. For three window types this is already determined.
For leeside ventilation, the wind direction proved to be a parameter of minor importance. Only a small effect was noticed for the windows with a relatively small length L_o. For the windward side ventilation, however, the effect of wind direction seems to be more pronounced.

The number of windows on the cover depends on the cover surface area and on the window to cover ratio A_o/A. An essential step in the research was

to investigate whether the ventilation function $G(\alpha)$ of the cover is dependent on the number of windows (i.e. the surface area) of the cover surface (chapter 3). Series of leeside ventilation measurements showed that the ventilation function $G(\alpha)$ is independent of the surface area (and so the number of windows). This indicates that the air exchange through a particular window is mainly driven by the pressure fluctuations across the window opening in question. So it can be concluded that there is no noticeable effect of ventilation from window to window. The absence of bypass-effects leads to the conclusion that every window that is opened contributes equally to the ventilation of the greenhouse.
A similar conclusion can be drawn from the study on the combined leeside and windward side ventilation (chapter 4). Apparantly there is no through-flow between the leeside and windward side windows in such a way that the fresh air by-passes the old. It appears that in case of the combined ventilation the total flux through the cover is the sum of the separate fluxes through the individual leeside and windward side window openings. This suggests that also for the combined ventilation the fluxes through the windows are caused by mainly the pressure fluctuations over the windows in question. The separate windward side and leeside ventilation characteristics therefore contain sufficient information to calculate the combined ventilation.
The above mentioned results are important for the development of a quantitative description of the ventilation of the 'quasi-infinite' covers: it appears that the total ventilation through the cover can be calculated from the measured ventilation function of the window type and the number of windows present on the cover.

Up to this point, much knowledge is amassed on the ventilation process of the windows equipped on a 'quasi-infinite' greenhouse cover. A clear understanding is gained how various greenhouse parameters and environmental factors act together and determine the ventilation flux. Parametrization of the theoretical model of the ventilation leads to a reliable quantitative description of the air exchange. For three window types the parametrization has been performed.
A next step in the research was to investigate whether the ventilation of greenhouses in actual practice can be understood on the basis of the ven-

tilation features of the 'quasi-infinite' greenhouse covers. The ventilation measurements in the enclosed compartments (chapter 3) show that, even though the locations of the compartments within the whole greenhouse complex were different, their ventilation features are very much the same. This suggests that the pressure fluctuations, established in the pressure fluctuation coefficient, are the same for the whole greenhouse cover. An additional effect on the ventilation, superimposed on the effect of the pressure fluctuations, is to be expected due to the finiteness of the cover.
The ventilation of several freestanding greenhouses with a different geometry and surface area was investigated (chapter 5). The results of the measurements show that the ventilation has increased compared to that of the enclosed greenhouse compartments, representing the 'quasi-infinite' cover. The increase of the ventilation is due to an effect, unknown up to now, which must be attributed to differences of the flow regime over the limited greenhouse cover and that over the 'quasi-infinite' cover.
Surprisingly, it was found that the relative difference between the ventilation of the greenhouse and that of the 'quasi-infinite' cover increases for the larger greenhouses. In this respect, both the upwind wall and the downwind surfaces of the greenhouse seem to be important. The measurements indicate that the ventilation model of the 'quasi-infinite' cover can well serve as a starting point for the description of the air exchange of the whole greenhouse. It seems that on the basis of the ventilation characteristics of the 'quasi-infinite' cover together with the given surface area of the greenhouse, an estimation can be made of the supplementary flux. In chapter 7 the general approach of our research and the main results are summarized and discussed.

SAMENVATTING

In dit proefschrift wordt de natuurlijke ventilatie van grote tuinbouwkassen bestudeerd. Het onderzoek richt zich met name op de ventilatie van Venlo-warenhuizen. Het kader en de doelstelling van het huidige onderzoek worden in hoofdstuk 1 toegelicht. Daarin wordt gesteld dat het kwantificeren van de luchtuitwisseling van de kassen van belang is voor de optimalisatie van de klimaatregeling in termen van de gewasproduktie en de energiebehoefte. Een eerdere studie van Bot (1983) over de ventilatie van Venlo-warenhuizen diende als uitgangspunt voor dit werk. In Bots dissertatie wordt een algemene beschrijving van de kasventilatie gepresenteerd. Veel parameters werden echter bepaald met behulp van schaalmodellen en ventilatiemetingen werden alleen uitgevoerd in een relatief klein kascompartiment.
Het onderzoek in dit proefschrift beoogt bouwstenen aan te dragen die een betrouwbare kwantitatieve beschrijving van de luchtuitwisseling van een willekeurig Venlo-warenhuis mogelijk maken. Dit vereist de in-situ bepaling en evaluatie van relevante parameters die een rol spelen in het ventilatieproces van de kassen.

De natuurlijke ventilatie van een gebouw wordt bepaald door de drukverdeling om het gebouw en de plaats en afmetingen van de (raam-) openingen. Het drukverschil over de openingen is de drijvende kracht voor de luchtuitwisseling. Dit drukverschil wordt veroorzaakt door wind- en temperatuureffecten. Het ventilatiedebiet wordt, behalve door het drukverschil, ook bepaald door de stromingsweerstand van de openingen. De stromingsweerstand van de raamopening in de kas is afhankelijk van de raamafmetingen en de openingshoek van het betrokken raam en vormt vanzelfsprekend een belangrijk onderdeel van de beschrijving van het ventilatieproces.

De ramen van de moderne ('multi-span') tuinbouwkassen liggen in een regelmatig patroon op het kasdek. De raamafmetingen variëren van kas tot kas, maar zijn over het algemeen voor één bepaalde kas hetzelfde. Een methode om de stromingsweerstand van de raamopeningen in de kas te beschrijven wordt besproken in hoofdstuk 2. Het eerste doel van ons onderzoek was deze beschrijving te toetsen aan in-situ metingen. De stromingsweerstand werd bepaald voor verschillende raamtypen en openingshoeken voor twee stromingsrichtingen (instroming en uitstroming). De resultaten van onze metingen waren in overeenstemming met de resultaten van eerder uitgevoerde metingen met schaalmodellen (Bot). Deze uitkomst staaft de gegeven beschrijving van de stromingsweerstand van de ramen die nu dus kan worden aanbevolen voor de beschrijving van de ventilatie door het kasdek.

Hoewel onder de meeste omstandigheden de windeffecten domineren, zijn de temperatuureffecten op de ventilatie van fundamenteel belang. De temperatuureffecten op de ventilatie door de raamopeningen zijn bestudeerd in hoofdstuk 6. De natuurlijke convectie is eerst gemeten voor rechthoekige openingen met verschillende lengte/breedte-verhoudingen in een horizontale en in een verticale wand. Op basis van deze resultaten werd een relatie geformuleerd voor de ventilatie door de raamopeningen tengevolge van temperatuureffecten. Uit ventilatieproeven bleek dat deze relatie de natuurlijke convectie door het raam goed weergaf. Vervolgens is een methode ontwikkeld om de ventilatie tengevolge van zowel wind- als temperatuureffecten te berekenen. In-situ metingen tonen aan dat deze methode in de praktijk goed te gebruiken is.

In de hoofdstukken 3, 4 en 5 wordt de invloed van de wind op de ventilatie bestudeerd. Omdat in de praktijk de lijzijde-luchting het meest wordt toegepast, krijgt deze vorm van ventilatie de meeste aandacht. Als uitgangspunt voor de beschrijving van de ventilatie door het gehele kasdek wordt de ventilatie van kascompartimenten beschouwd die relatief ver van de zijgevels verwijderd zijn. Het dek van zo'n compartiment wordt quasioneindig genoemd. Er wordt verondersteld dat het stromingsveld rond elke kap (en raamopening) gelijk is en dat er geen statische drukverschillen optreden tussen de ramen onderling. Er wordt als het ware van uitgegaan dat het dek zich gedraagt als een dek zonder randeffecten.
Een beschrijving van de luchtuitwisseling door zo'n quasi-oneindig dek wordt gepresenteerd in hoofdstuk 3. In deze beschrijving wordt de ventilatie door de ramen uitgedrukt in een ventilatiefunctie $G(\alpha)$. Deze functie relateert het ventilatiedebiet per eenheid raamoppervlakte aan de

gemiddelde windsnelheid (op referentiehoogte) en de raamopening. Vervolgens zijn ventilatiemetingen uitgevoerd in compartimenten waarvan het dek als quasi-oneindig kan worden beschouwd. Deze metingen gaven veel inzicht in het ventilatieproces. De invloed van de windrichting, windsnelheid en de raamafmeting werd bestudeerd.

De resultaten van de ventilatiemetingen kwamen goed overeen met de in hoofdstuk 3 gegeven beschrijving van de ventilatie. Een lineair verband werd aangetoond tussen het ventilatiedebiet en de gemiddelde windsnelheid op referentiehoogte bij lijzijde- en loefzijde-luchting (hoofdstuk 3 en 4). De ventilatiefunctie $G(\alpha)$ is experimenteel bepaald voor ramen met verschillende afmetingen op een quasi-oneindig dek. Deze ventilatiefunctie verschilt per raamtype. Deze verschillen kunnen slechts gedeeltelijk verklaard worden door de verschillen in de stromingsweerstanden van de gebruikte raamtypen. Uit de metingen blijkt echter dat ook de drukfluctuatiecoëfficiënt $K_f(\alpha)$ voor elk raamtype verschillend is. Dit wijst erop dat de raamafmetingen en de raamopeningshoek een dubbele rol spelen in het ventilatieproces: ze bepalen de stromingsweerstand van de raamopening èn ze beïnvloeden de relatie tussen de kinetische energie van het windveld op referentiehoogte en de optredende drukfluctuaties bij het raam. Dit betekent dat de ventilatiefunctie voor een willekeurig raamtype niet a priori voorspeld kan worden, zelfs al is de stromingsweerstand van dat raam bekend. Daarvoor is meer inzicht nodig in het gedrag van de drukfluctuatiecoëfficiënt K_f als functie van de raamafmetingen en de openingshoek. Voor drie raamtypen is dit in het proefschrift bepaald.
De windrichting heeft bij lijzijde-luchting weinig invloed op de ventilatie. Slechts voor ramen met een relatief kleine lengte L_o lijkt er een effect te bestaan van de windrichting op de ventilatie. Bij loefzijde-luchting is het effect van de windrichting op de ventilatie groter.

Het aantal ramen op het kasdek wordt vastgelegd door de oppervlakte van het dek en de verhouding tussen de totale oppervlakte van de ramen en die van het totale dek (A_o/A). Een belangrijke stap in de beschrijving van de luchtuitwisseling door het quasi-oneindige dek was te onderzoeken of de ventilatiefunctie $G(\alpha)$ afhangt van het aantal ramen en dus van de oppervlakte van het dek (hoofdstuk 3). Een serie metingen bij lijzijde-luchting

laat zien dat de ventilatiefunctie $G(\alpha)$ niet beïnvloed wordt door het aantal ramen en de oppervlakte van het (quasi-oneindige) dek. Dit beduidt dat de luchtuitwisseling door elk raam bepaald wordt door de drukfluctuaties over het raam zelf en dat elk geopend raam in gelijke mate bijdraagt tot de totale ventilatie.
Een dergelijke conclusie kan ook getrokken worden uit een onderzoek van de ventilatie bij gecombineerde lijzijde- en loefzijde-luchting (hoofdstuk 4). De resultaten van dit onderzoek tonen aan dat de totale ventilatie beschouwd kan worden als de som van de afzonderlijke lijzijde- en loefzijde-luchting. Er is geen effect waargenomen dat wijst op doorstroming van de lucht tussen de ramen aan de verschillende zijden van de kappen. Deze resultaten wijzen erop dat ook in het geval van de gecombineerde lijzijde- en loefzijde-luchting de ventilatie door elk raam veroorzaakt wordt door de drukfluctuaties over het raam in kwestie. De afzonderlijke lijzijde- en loefzijde-ventilatiefuncties geven derhalve voldoende informatie voor de berekening van de gecombineerde ventilatie.
De bovengenoemde resultaten zijn belangrijk om tot een goede kwantitatieve beschrijving van de luchtuitwisseling van een quasi-oneindig dek te komen: het blijkt dat de totale ventilatie door het dek berekend kan worden uit de gemeten ventilatiefuncties van het betreffende raamtype en het aantal ramen op het dek.

Tot dusver is het onderzoek beperkt gebleven tot het ventilatieproces door de ramen op een quasi-oneindig kasdek, waarover veel kennis is verworven. Het is duidelijk geworden hoe de verschillende kas-parameters en de omgevingsfactoren een rol spelen in het ventilatieproces en hoe zij het ventilatiedebiet bepalen. Voor drie raamtypen is de theoretische beschrijving van de ventilatie geparametriseerd. Dit leidde tot een betrouwbare weergave van de luchtuitwisseling door de betrokken ramen.
De volgende stap was te onderzoeken of de ventilatie van de kassen in de praktijk begrepen en beschreven kan worden op basis van de ventilatie door het quasi-oneindige dek. De ventilatiemetingen in de verschillende compartimenten (met een quasi-oneindig dek) in hoofdstuk 3 lieten een gelijk ventilatiegedrag zien, ofschoon hun plaats binnen het kascomplex erg verschillend was. Dit wijst erop dat de drukfluctuaties, vastgelegd in de

drukfluctuatiecoëfficiënt, gelijk zijn over het hele dek. Het mag echter worden verwacht dat de aanwezigheid van de zijgevels (m.a.w. de eindigheid van de kas) een effect zal hebben op de ventilatie door het dek. Verondersteld wordt dat dit additionele effect gesuperponeerd kan worden over het effect van de drukfluctuaties. Om dit te onderzoeken zijn ventilatiemetingen uitgevoerd in verschillende vrijstaande kassen met verschillende oppervlakten en lengte/breedte-verhoudingen (hoofdstuk 5). De metingen tonen aan dat de ventilatie van het kasdek relatief groter is dan de ventilatie door het dek van een compartiment met een quasi-oneindig dek. Deze toename van de ventilatie is het gevolg van een (tot nu toe nergens beschreven) effect dat toegeschreven moet worden aan de verschillen in stromingspatronen over het quasi-oneindige dek en het eindige kasdek. Opmerkelijk was het feit dat het relatieve verschil tussen de ventilatie van de kas en de ventilatie van het quasi-oneindige dek toenam voor grotere kassen. Dit is gemeten in kassen met een sterk verschillende lengte/breedte-verhouding. Dit beduidt dat niet alleen de afmeting van de gevel aan de windzijde, maar ook de afmeting van de andere gevels en van het dekoppervlakte van belang zijn voor de toename van de ventilatie.
De metingen tonen aan dat de ventilatiebeschrijving voor het quasi-oneindige dek goed kan dienen als uitgangspunt voor de beschrijving van de ventilatie van de gehele kas. Het lijkt erop dat op basis van het ventilatiegedrag van een quasi-oneindig dek en de oppervlakte van de kas een schatting gemaakt kan worden van het additionele effect van de gevels en zo van de totale ventilatie van de kas. In hoofdstuk 7 worden de belangrijkste conclusies en de onderzoeksmethode geresumeerd en besproken.

LIST OF SYMBOLS

A = surface area (m^2)

A_a = additional surface area (m^2)

A_o = area of ventilating windows (m^2)

A_w = effective opening area of the one-side-mounted window (m^2)

b = breadth (m)

c = concentration of tracer in enclosure ($kg \cdot m^{-3}$)

c_i = initial concentration of tracer in enclosure ($kg \cdot m^{-3}$)

c_a = ambient tracer concentration ($kg \cdot m^{-3}$)

C = discharge coefficient (-)

C_f = discharge coefficient for the flux through the front area of the one side-mounted window (-)

d = thickness (m)

$f_1(\alpha)$ = function defined by eqn. 2.3a (-)

$f_2(\alpha)$ = function defined by eqn. 2.3b (-)

$f_w(\alpha)$ = window function defined by eqn. 2.5 (-)

F_o = friction factor of the rectangular opening (eqn. 2.1) (-)

F_w = friction factor of the window opening (-)

g = gravitational acceleration ($m \cdot s^{-2}$)

$G(\alpha)$ = ventilation function defined by eqn. 3.8 (-)

H or h = height (m)

H_o = height of the rectangular opening (m)

K_p = pressure coefficient defined by eqn. 3.1 (-)

$K_f(\alpha)$ = pressure fluctuation coefficient defined by eqn. 3.2 (-)

L or l = length (m)

L_o = length of rectangular opening (m)

n = rotation velocity of propeller ($rad \cdot s^{-1}$)

p = perimeter (m)

P = pressure ($N \cdot m^{-2}$)

P_u = static time averaged pressure ($N \cdot m^{-2}$)

ΔP_{i-o} = pressure difference across inlet and outlet blower ($N \cdot m^{-2}$)

R = ventilation rate (s^{-1}) or (h^{-1})

Re = Reynolds number (-)

t = time (s)

T = temperature (K)

u = outside windspeed ($m \cdot s^{-1}$)

v = velocity of air ($m \cdot s^{-1}$)

V = volume (m^3)

w = width (m)

α = window opening angle (deg)

β = thermal expansion coefficient (K^{-1})

Δ = difference (-)

ρ = density ($kg \cdot m^{-3}$)

ρ_o = density of air in the opening ($kg \cdot m^{-3}$)

ρ_a = density of ambient air ($kg \cdot m^{-3}$)

Φ_v = air volume flux or ventilation flux ($m^3 \cdot s^{-1}$)

$\Phi_{v,C}$ = ventilation through the greenhouse cover caused by pressure fluctuations only (eqn. 5.1) ($m^3 \cdot s^{-1}$)

$\Phi_{v,G}$ = total ventilation of the greenhouse (eqn. 5.1) ($m^3 \cdot s^{-1}$)

$\Phi_{v,L}$ = leakage ventilation (eqn. 5.1) ($m^3 \cdot s^{-1}$)

$\Phi_{v,S}$ = supplementar flux due to 'side wall effect' (eqn. 5.1) ($m^3 \cdot s^{-1}$)

Φ_m = mass flux ($kg \cdot s^{-1}$)

Ψ = roof slope angle (deg)

superscript

~ amplitude

- average value

CURRICULUM VITAE

Taeke de Jong werd op 3 juni 1958 geboren in Leeuwarden. Na voltooiing van de Atheneum B opleiding aan de Scholengemeenschap Zuid te Enschede begon hij in 1976 de studie Landbouwtechniek aan de Landbouwuniversiteit Wageningen. Het propaedeutisch examen werd gehaald in 1977. De studie werd in 1979 vervolgd en in 1985 afgerond. Tijdens de doctoraalfase heeft de nadruk gelegen op de natuurkunde (technische natuurkunde, meet-, regel- en systeemtechniek en een praktijk verbonden aan de vakgroep Natuurkunde van de Universiteit van Évora, Portugal). Daarnaast kwamen teelttechnische aspecten aan de orde (landbouwplantenteelt en grondbewerking).
In 1985 volgde in het kader van een promotieonderzoek de aanstelling als wetenschappelijk medewerker in tijdelijke dienst binnen de sectie Natuurkunde van de toenmalige vakgroep Natuur- en Weerkunde (thans deel uitmakende van de vakgroep Agrotechniek en -fysica). Van 1986 tot 1988 was hij gedetacheerd aan het Proefstation voor Tuinbouw onder Glas (PTG) te Naaldwijk (afdeling teelt en kasklimaat).