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Air exchange caused by wind effects through (window) openings distributed evenly on a quasi-infinite surface

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Abstract

A theoretical approach is presented to describe the air exchange through (window) openings located at positions with the same external pressure. Next, we measured the air exchange through a series of window openings distributed on a quasi-infinite surface. The results of these full-scale measurements are in agreement with the predictions based on the given representation. The presented approach is applied, in combination with an empirical model describing the flow characteristics of one-side-mounted windows, to discuss the measured air exchange through open windows with different geometries.

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 control of the indoor climate. Consequently, the process of natural ventilation is a topic of engineering interest for the thermal design and climate control of buildings such as greenhouses, schools, offices, storage depots.

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. The present paper is 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 [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, $1/2\ \rho_a \bar{u}^2$, according to:

$$P_u = C_p \times \frac{1}{2} \rho_a (\bar{u})^2 \qquad (1)$$

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

When the ventilation openings are located at positions with different pressure (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

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openings are located at positions in a surface with the same external pressure 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 C_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 [2–9]. 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 [10]. 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 between the pressures generated at each opening, may result in momentary pressure differences and thus also have an effect on the airflow 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 authors, 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 paper, 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 paper, 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 and 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 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 [11], was employed to evaluate the results of the experiments.

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 since this type of ventilation provides a more equable air infiltration as compared to the windward side ventilation.

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 [12] 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 $\tilde{P}$ 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. (1):

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

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. Note 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 recently presented by De Jong and Bot [11]. They derived a relationship between the pressure difference over the window opening (ΔP) and the corresponding volume flux under the window flap (ϕ_v)

$$\Delta P = \left(\frac{F_0}{f_w(\alpha)}\right) \times \frac{1}{2}\rho_0\left(\frac{\phi_v}{A_0}\right)^2 \tag{3}$$

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

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 eqns. (2) and (3) 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:

$$\frac{\phi_v}{\bar{u}A_0} = \frac{1}{2}\left[\frac{K_f(\alpha) f_w(\alpha)\rho_a}{F_0\rho_0}\right]^{1/2} \tag{4a}$$

which can be written as:

$$\frac{\phi_v}{\bar{u}A_0} = G(\alpha) \tag{4b}$$

Equation (4b) states that a linear proportionality exists between the air flux ϕ_v and wind speed $\bar{u}$ 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_0 and $f_w(\alpha)$, and the pressure fluctuation coefficient $K_f(\alpha)$ near the windows. Obviously, the ratio (ρ_a/ρ_0) 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 wind speed at reference level, dependent upon 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, airflows 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. (4). 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. Ventilation through a fixed number of openings

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 C_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

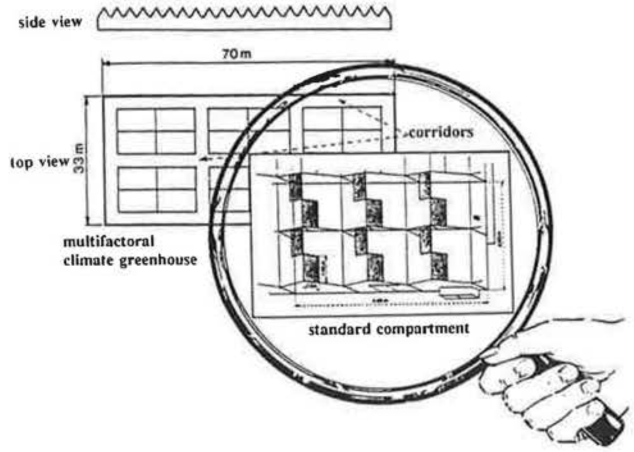

Fig. 1. Large greenhouse block with 24 standard compartments.

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 (70×33 m^2, Fig. 1), surrounded by identical glasshouses and situated at the Glasshouse Crops Research Station, Naaldwijk, The Netherlands, [13]. These compartments are equipped with windows with dimensions $L_0 = 1.46$ m and $H_0 = 0.80$ m and hinged from the ridge on both sides of the span.

In our experiments, we apply the decay rate method. The tracer gas 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, the mean wind speed and wind direction at a reference level of 10 m (located near the glasshouse block) were measured on a minute base (relatively fast compared to the decrease of tracer). During the experiments no crops were grown in the compartments.

3.2. *Results and discussion*

In Fig. 2, 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 suggests that a continuous effective ventilation flux is found. This despite the fluctuating character of the wind. In Fig. 3(a)–(d) a representative selection from the measured leeside ventilation results for some window openings of the standard compartment is shown. The wind direction during the measurements was separated into two angles with respect to the window on the cover according to the Figure.

From Fig. 3(a)–(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. (4). 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 a study on ventilation due to thermal effects [14], 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. 4. It shows that the compartments are well sealed since the measured leakage ($\alpha = 0°$) is close to zero. When the windows are opened up to 15°, 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 $G(\alpha)$ can be fitted through the measuring points:

$$G(\alpha) = 2.29 \times 10^{-2} \, [1 - \exp(-\alpha/21.1)] \qquad (5)$$

The results are in agreement with those of Bot [12] and Nederhoff *et al.* [15], 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 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:

$$\phi_v = \phi_m/(c - c_a) \qquad (6)$$

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 the decay rate and static tracer-gas method are based on a perfect mixing of the inside air.

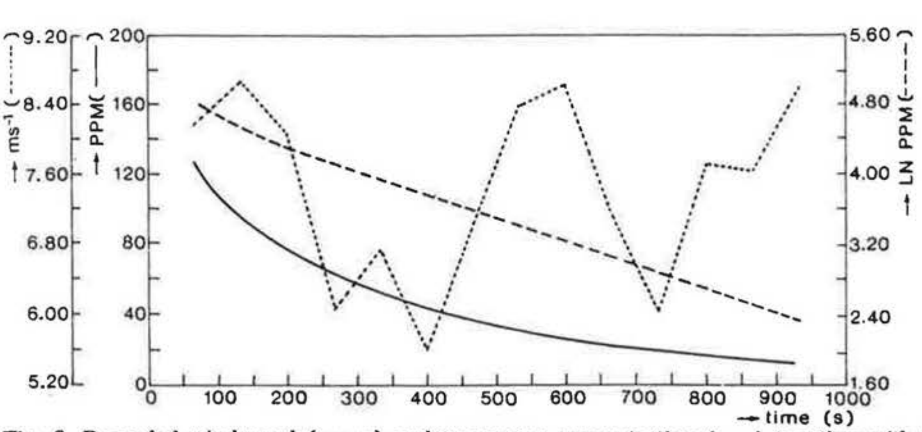

Fig. 2. Recorded windspeed (·····) and tracer gas concentration (——) together with its natural logarithm (– – –) during one measuring period.

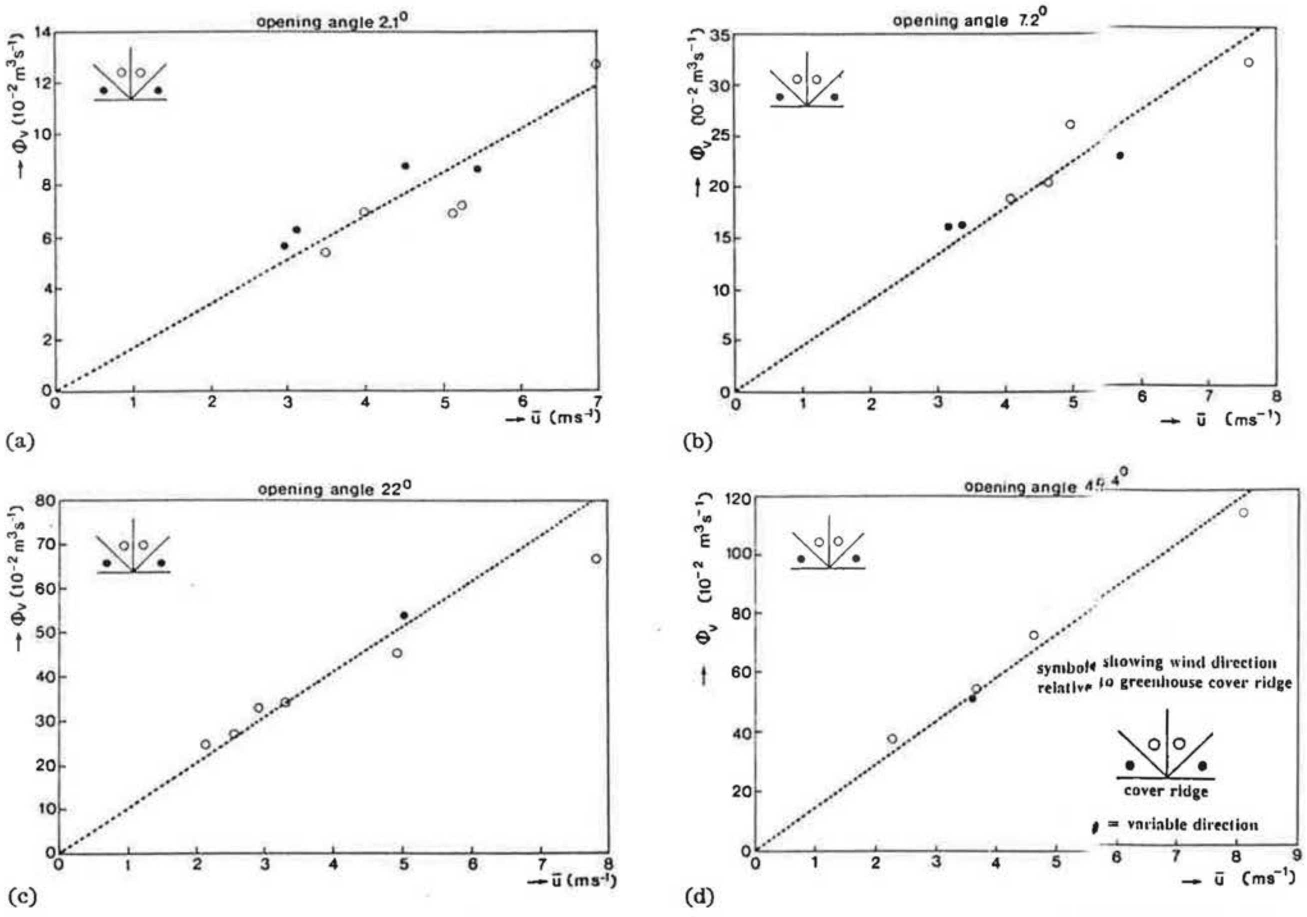

Fig. 3. Ventilation flux in the compartment as a function of the average wind speed at various window apertures. The wind direction is specified on each graph.

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 corners). The major advantage of the constant flow method is that the problem of the unknown effective volume does not matter according to eqn. (6). 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

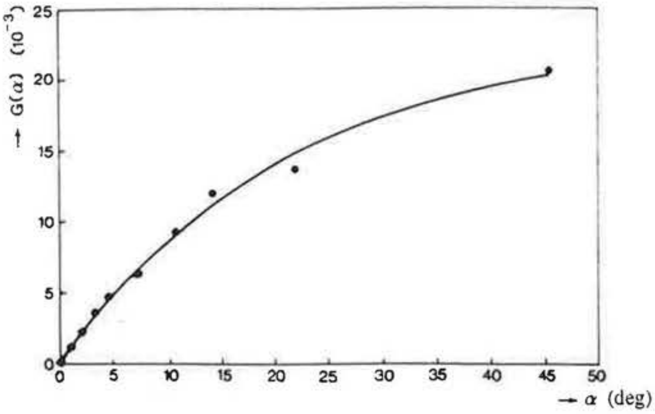

Fig. 4. Measurements and fit of ventilation flux over wind speed (normalized per unit area of ventilation windows (A_o)) as a function of the window opening.

as:

$$G(\alpha)=1.07\times10^{-3}\ \alpha\exp(-\alpha/50) \quad (7)$$

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 are 1.03×10^{-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.

4. Ventilation through different numbers of openings

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. 1) 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.

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 (containing 4 and 8 windows) respectively, were available in addition to the standard compartment (Fig. 5). The ventilation fluxes through the window openings of the compartments were measured in the same way as described in Section 3.

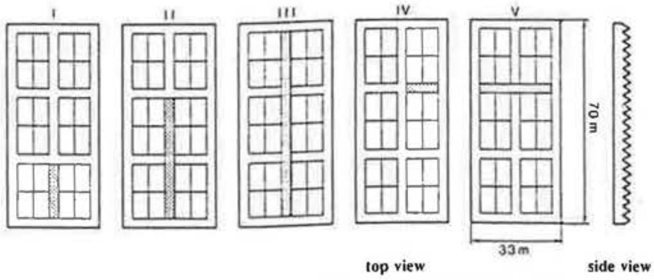

Fig. 5. Constructed compartments in the corridors of the greenhouse block.

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 $G(\alpha)$ according to eqn. (4b). 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 6(a) shows the measured ventilation fluxes expressed as $G(\alpha)$ 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, $G(\alpha)$ is presented in Fig. 6(b). A comparison of the measurements in all compartments, including the standard compartment (VI), is made in Fig. 6(c).

Figure 6(a) 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 Fig. 6(b) 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

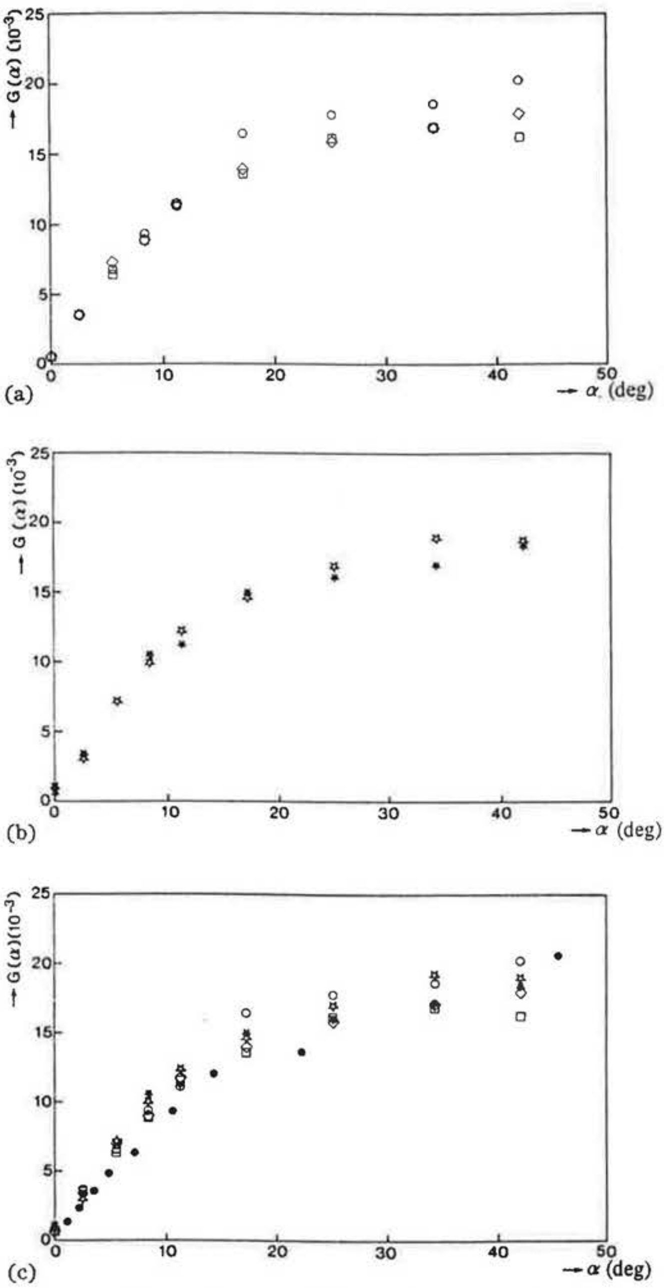

Fig. 6. (a) Measured values of the ventilation function $G(\alpha)$ for the compartments I–III: □ = compartment I, ◇ = compartment II, ○ = compartment III. (b) Measured values of the ventilation function $G(\alpha)$ for the compartments IV and V: ★ = compartment IV, ☆ = compartment V. (c) Measured values of the ventilation function $G(\alpha)$ for the compartments I–VI: ● = compartment VI, other symbols as indicated in Fig. 6(a) and 6(b) captions.

sealed carefully, and it is this sealing of the cover that was not performed for compartments I–V in the corridors.

The higher air leakage rate of compartments I–V may have resulted in an increase of the measured ventilation for all window openings. Indeed, from Fig. 6(c) 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 measuring greater 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 vicinity 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.

5. The effect of the window geometry on the ventilation

5.1. Considerations

The effect of the window geometry of the one-side-mounted window on the ventilation characteristics through the window opening (eqn. (4)) is expressed in the window variables F_0, $f_1(\alpha)$ and $f_2(\alpha)$. The ratio of the length and height of the window opening appears to be of cardinal importance [11]. 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. (4)) for leeside ventilation through windows with aspect ratio 1.825 ($L_0 = 1.46$ m and $H_0 = 0.80$ m) was already experimentally determined in Sections 3 and 4. This data will be discussed in this Section in connection with the leeside ventilation measurements through windows with aspect ratio 1.00 ($L_0 = H_0 = 0.71$ m) and 0.47 ($L_0 = 0.73$ m and $H_0 = 1.55$ m).

The window variables F_0, $f_1(\alpha)$ and $f_2(\alpha)$ are affected by the aspect ratio. In Section 2, it was suggested that this also holds for the pressure fluctuation coefficient $K_f(\alpha)$. It is difficult to determine or estimate this effect a priori. 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 of De Jong and Bot [11]) and the ventilation function $G(\alpha)$ (determined from the ventilation experiments in Sections 3 and 4) according to eqn. (4). For that purpose eqn. (4) can be rearranged to:

$$K_f(\alpha) = \frac{4\rho_0 F_0[G(\alpha)]^2}{\rho_a f_w(\alpha)} \tag{8}$$

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 wind speed.

5.2. *Experimental set-up*

The new measurements were performed in an airtight compartment constructed in the centre of a greenhouse block [11]. 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 aspect ratio either 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 3.1. During the measurements, no crop was present and the compartment was unheated.

5.3. *Results and discussion*

Analysis of the measurements shows that the effect of the temperature difference between the inside and outside air on the total ventilation can be regarded as small, as compared to the wind effect.

According to eqn. (4), 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 3.2 and 4.2). 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. 7. 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 seems 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. 8(a) and (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 ratios 1.00 and 0.47. Possibly the eddy size of the turbulent wind in relation to the length of the window (L_0) 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. 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 $G(\alpha)$ of the windows with aspect ratios 1.825, 1.00 and 0.47 are collected in Fig. 9. For the windows with aspect ratios 1.00 and 0.47, these functions were calculated analogous to eqn. (5). 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:

$$G(\alpha) = 2.62 \times 10^{-2}\ [1 - \exp(-\alpha/14.6)] \tag{9}$$

for the window with aspect ratio 1.00, and:

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

for the window with aspect ratio 0.47.

Figure 9 shows that for the windows with the smaller aspect ratios, the initial increase of the ventilation function $G(\alpha)$ is faster than for windows with higher aspect ratios. This effect can, at least partly, be explained by the flow characteristics of the windows. In particular, the greater effect of the side areas of the windows with smaller aspect ratios should be mentioned.

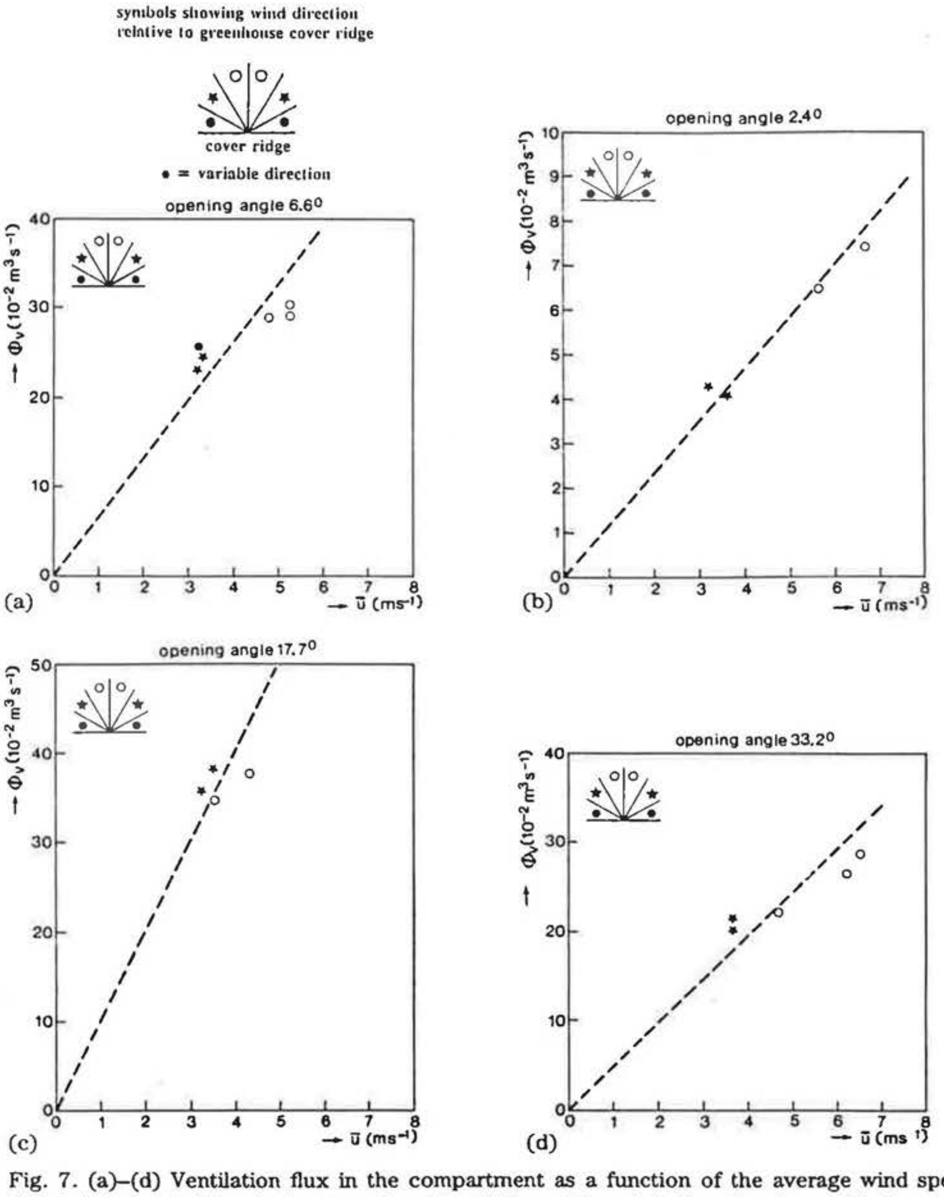

Fig. 7. (a)–(d) Ventilation flux in the compartment as a function of the average wind speed. (a)–(b): window type $L_0 = 0.73$ m, $H_0 = 1.46$ m, (c)–(d): window type $L_0 = H_0 = 0.71$ m. The wind direction is specified on each graph.

However, the window parameters F_0 and $f_w(\alpha)$ alone do not fully explain the measured ventilation characteristics of the various windows. From the experimentally obtained ventilation function $G(\alpha)$, the pressure fluctuation coefficient $K_f(\alpha)$ can be calculated according to eqn. (8) for the various window types. These pressure fluctuation coefficients $K_f(\alpha)$ are presented in Fig. 10 for the window geometries under study. When this coefficient was defined in eqn. (2), it was already suggested that its value could be affected by the geometry of the surface and (therefore) also by the window-type and opening angle. This seems to be confirmed by our experimental results.

It appears that both the pressure fluctuation coefficient $K_f(\alpha)$ and the flow characteristics of the windows (determined by the window parameters $f_w(\alpha)$ and F_0) 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. Apparently, 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

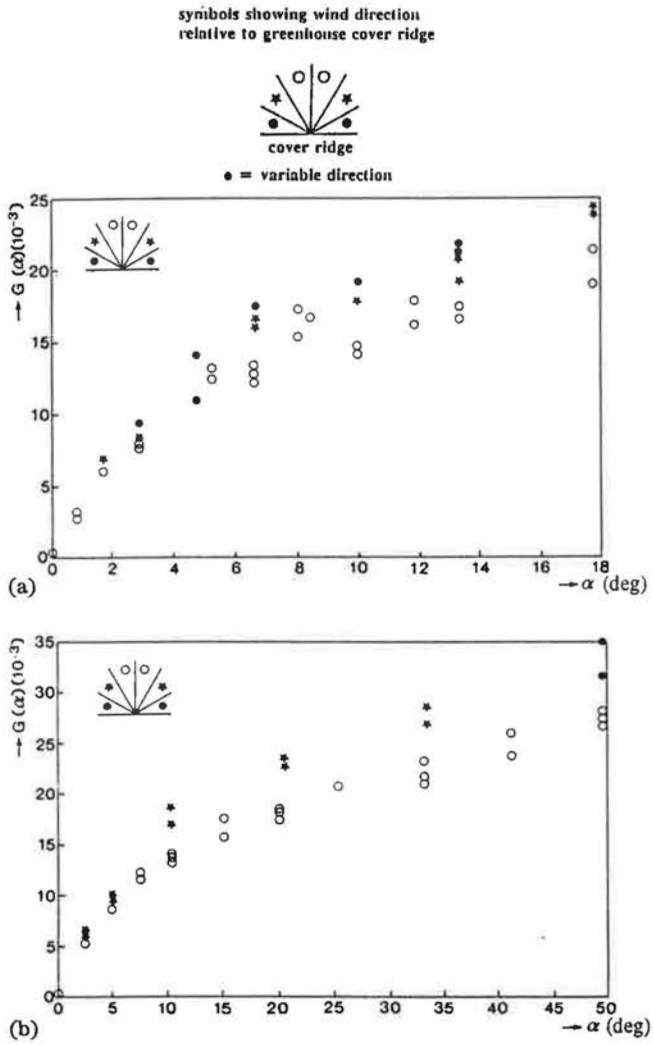

Fig. 8. (a) Values of the ventilation function $G(\alpha)$ for the window with aspect ratio 0.47. The wind direction is classified on each graph. (b) Values of the ventilation function $G(\alpha)$ for the window with aspect ratio 1.00. The wind direction is classified on each graph.

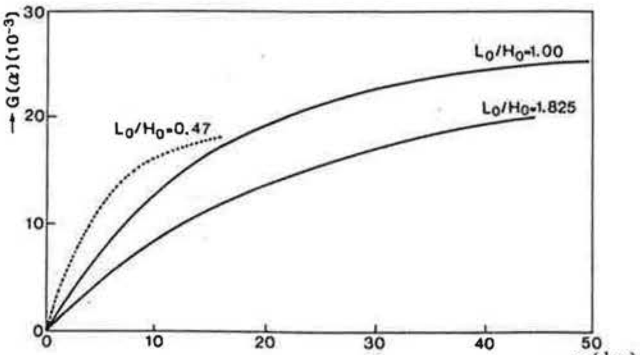

Fig. 9. Ventilation functions $G(\alpha)$ of the windows with aspect ratio 1.825, 1.00 and 0.47.

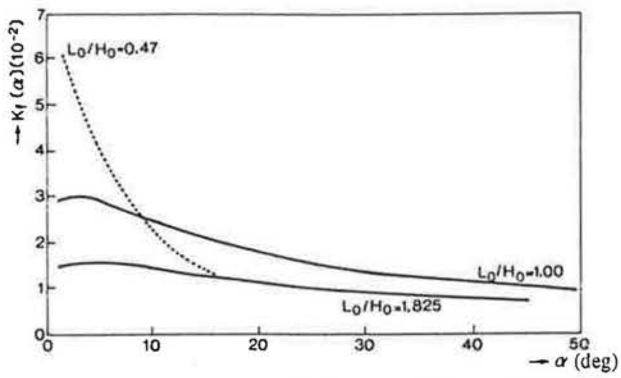

Fig. 10. The pressure fluctuation coefficients $K_f(\alpha)$ for the windows under study.

pressure fluctuation coefficient is related to the local flow field and, so, to the geometry of the surface and the dimensions of the window.

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 coefficients, 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.

Nomenclature

A_0	opening area of rectangular opening (m^2)
c	concentration of the tracer in the enclosure (kg m^{-3})
c_a	ambient tracer concentration
$f_1(\alpha)$	F_w/F_0
$f_2(\alpha)$	A_w/A_0
$f_w(\alpha)$	$[f_2(\alpha)]^2/f_1(\alpha)$
F_0	friction factor of rectangular opening
F_w	friction factor of window opening
$G(\alpha)$	ventilation function defined by eqn. (4) (–)
H_0	height of rectangular opening (m)
C_p	pressure coefficient defined by eqn. (1) (–)
$K_f(\alpha)$	pressure fluctuation coefficient defined by eqn. (2) (–)
L_0	length of rectangular opening (m)
ΔP	pressure difference across the opening (N m^{-2})
P_u	static time average pressure (N m^{-2})
$\tilde{P}_u$	amplitude of the pressure fluctuations (N m^{-2})
$\bar{u}$	average wind speed at reference level (m s^{-1})
$\bar{v}$	average air velocity in opening (m s^{-1})
α	window opening angle (deg)
ρ_0	density of air in the opening (kg m^{-3})
ρ_a	density of ambient air (kg m^{-3})
ϕ_v	air volume flux or ventilation flux (m^3 s^{-1})
ϕ_m	mass flux of injected tracer gas (kg s^{-1})

References

1 J. B. Dick, The fundamentals of natural ventilation of houses, *J. Inst. Heat. Vent. Engs.*, *18* (1950) 123–134.

2 J. E. Hill and T. Kusuda, Dynamical character of air infiltration, *ASHRAE Trans.*, *81* (1975) 168–185.

3 J. P. Cockroft and P. Robertson, Ventilation of an enclosure through a single opening, *Build. Environ.*, *11* (1976) 29–35.

4 P. R. Warren, Ventilation through openings in one wall only, *Proc. 1977 ICHMT Seminar on Heat Transfer in Buildings*, Hemisphere, NY, 1977.

5 P. R. Warren, The analysis of single-sided ventilation measurements, *Air Infiltr. Rev.*, *7* (2) (1986).

6 M. Narasaki, T. Yamanaka and M. Higuchi, Influence of turbulent wind on ventilation, Preprint for Indoor Air 87 Conf., Berlin, August 17–21, 1987.

7 D. W. Etheridge and D. K. Alexander, The British Gas Multi Cell Model for calculating ventilation, *ASHRAE Trans.*, *86* (1980) 808–821.

8 F. Haghighat, J. Rao and P. Fazio, The influence of turbulent wind on air change rates—a modelling approach, *Build. Environ.*, *26* (2) (1991) 95–109.

9 J. Riberon, D. Bienfait, G. Barnaud and J. Villain, Effect of wind pressure fluctuations on air movements inside buildings, *Proc. 11th AIVC Conf., Belgirate, Italy, 1991.*

10 H. K. Malinowski, Wind effect on air movement inside buildings, Paper presented at *Tokyo Conference of Wind Loads, Tokyo, Japan, September 6, 1971.*

11 T. de Jong and G. P. A. Bot, Flow characteristics of one side-mounted windows, *Energy Build.*, *19* (1992) 105–113 (this issue).

12 G. P. A. Bot, Greenhouse climate: from physical processes to a dynamical model, *Dissertation*, Agricultural University, Wageningen, 1983, 240 pp.

13 J. van de Vooren and R. Koppe, The climate glasshouse at Naaldwijk, Neth., *J. Agric. Sci.*, *23* (1975) 238–247.

14 T. de Jong, Air exchange due to temperature effects through one-side-mounted windows, (in preparation).

15 E. M. Nederhoff, J. van de Vooren and A. J. Udink ten Cate, A practical tracer gas method to determine ventilation in greenhouses, *J. Agric. Eng. Res.*, *31* (4) (1985) 309–319.