

Theoretical study of natural ventilation flux in a single span greenhouse

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The ventilation flux was calculated for single span greenhouses with single longitudinal roof opening and with both longitudinal roof and vertical side wall openings. Thermal buoyancy and wind pressure contributions were separately analysed and then combined for lee-side as well as for windward side ventilation. For the single roof window, the temperature effect, proportional to the square root of the temperature difference, becomes negligible when compared to the wind effect, proportional to the wind speed, as soon as this is higher than $1.5 \text{ m}\cdot\text{s}^{-1}$. When a vertical side wall opening was added to the roof window, the temperature effect was enhanced by the so called chimney effect, linked with the vertical distance between the two openings, in such a way that it becomes negligible only for an external wind speed higher than $4 \text{ m}\cdot\text{s}^{-1}$.

Keywords. Greenhouse, natural ventilation, wind and temperature effects.

Étude théorique du flux de ventilation naturelle dans une serre à une seule chapelle. On calcule le flux de ventilation de serres à une seule chapelle équipées, soit d'une ouverture longitudinale faîtière unique, soit d'une ouverture faîtière et d'une ouverture longitudinale dans la paroi latérale. On analyse séparément les contributions de l'effet de température et de la pression dynamique du vent pour les combiner ensuite, tant dans le cas de la ventilation sous le vent que face au vent. Pour l'ouverture faîtière, l'effet de température, proportionnel à la racine carrée de la différence de température, devient négligeable comparé à l'effet du vent, proportionnel à sa vitesse, dès que celle-ci dépasse $1,5 \text{ m}\cdot\text{s}^{-1}$. Quand une ouverture latérale est ajoutée à l'ouverture faîtière, l'effet de température est amplifié par l'effet de cheminée lié à la distance verticale entre ces deux ouvertures et il ne devient négligeable que pour une vitesse du vent supérieure à $4 \text{ m}\cdot\text{s}^{-1}$.

Mots-clés. Serre, ventilation naturelle, effets du vent et de la température.

INTRODUCTION

Natural ventilation in greenhouses has been studied theoretically and experimentally for a long time. The two main driving forces of air exchange were identified as the thermal buoyancy and the wind induced forces (or stack and wind effects). In order to have a better understanding of the ventilation mechanism, these driving forces were treated separately and two particular single span greenhouses were investigated: the single sided longitudinal roof opening case and the case of a roof opening with a longitudinal side wall opening.

The theories of natural ventilation were developed and understood for cases in which only thermal buoyancy or only wind pressure exists in buildings. The calculation of ventilation rate only due to thermal buoyancy was performed by Emswiler (1962), Bruce (1977) and Randall and Patal (1994). The wind effect on the ventilation was determined by the internal and external pressure coefficients as functions of wind direction and the building configuration (Bruce, 1975;

Shrestha *et al.*, 1993). The combined temperature and wind effects were carried out in different ways (Lee *et al.*, 1982; Perera, 1986; Zhang *et al.*, 1989; Albright *et al.*, 1992; Walker, Wilson, 1993). In greenhouses, a few studies for predicting ventilation flux were available for a roof ventilator (Bot, 1983; De Jong, 1990; Boulard, Baille, 1995), or for both roof and side openings (Kozai, Sase, 1978). From these studies we might conclude that the proposed calculations were restricted within narrow ranges for particular houses with special vents. Thus the results were not completely covering the various situations. The complicated interactions between temperature and wind effects were not fully clarified.

The purpose of this paper was to develop a method to calculate the ventilation flux due to the effects of both thermal buoyancy and wind pressure based on the following assumptions: steady state, the air being an ideal, inviscid and incompressible gas as well as uniform temperature distribution in the whole greenhouse. This study focused firstly on the greenhouse with a single

longitudinal roof opening and then on the greenhouse with both roof and side wall openings.

In the former case, the ventilation fluxes induced by temperature or wind effect were analysed and compared in detail on the basis of interior-exterior air temperature difference, the absolute temperatures, the roof opening angle and the external wind speed. Four different methods to combine the temperature and wind effects were compared.

In the latter case, the chimney effect due to the air temperature difference between inside and outside of the greenhouse was analysed as a function of the distance between the roof and the side wall openings and the opening angles of both windows. The combined effect of temperature and wind on the ventilation was finally investigated by the pressure distribution method.

GREENHOUSE WITH A SINGLE LONGITUDINAL ROOF OPENING

The simplest situation in greenhouses, as far as natural ventilation is concerned, is the single roof window with a homogeneous temperature field inside (T_i) and outside (T_e) (Figure 1). The studied greenhouse was a single span with a roof angle $\alpha = 22^\circ$. The window was characterized by a width (H_0) and an opening angle β . Its length (L_0) was the greenhouse overall length. See also list of symbols at the end of the article.

Temperature effect

When the longitudinal greenhouse window was open, the air exchange due to temperature effect occurred mainly through the front aperture of vertical height h with length L_0 and increased with the opening angle. The thermal pressure in the greenhouse window varied with the distance z (Figure 1) and the pressure difference at each level in the opening,

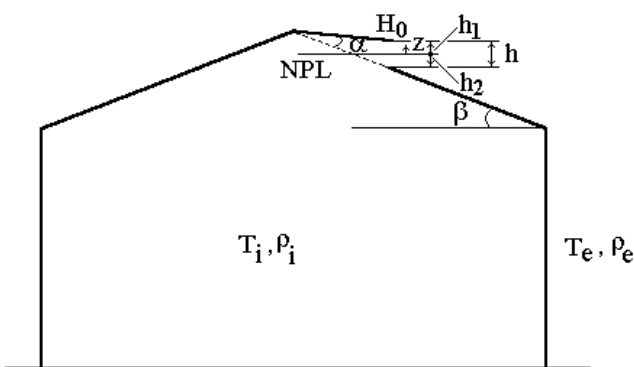


Figure 1. Scheme of an opening under the ventilation window on the roof — Schéma de l'ouverture sous une fenêtre de ventilation en toiture.

between in- and outside due to density difference resulted in air exchange and was given by:

$$P_T(z) = - (\rho_i - \rho_e) g z \tag{1}$$

$$= - \frac{(\rho_i - \rho_e)}{\rho_e} g z$$

According to the mass balance (inflow and outflow are to be equal), the neutral pressure level (NPL) will be found where the interior and exterior pressures become equal. Therefore, the ventilation flux can be calculated by integrating the air speed through the lower part of the opening (below NPL) or the upper part of the opening (above NPL). The distribution of air speed $v(z)$ through the opening can be deduced from equation (1):

$$v(z) = C_d \sqrt{\frac{2}{\rho_e} P_T(z)} \tag{2}$$

$$= C_d \sqrt{\frac{2 g}{\rho_e} (\rho_i - \rho_e) z}$$

$$= m \sqrt{z} \quad \text{with } m = C_d \sqrt{\frac{2 g}{\rho_e} (\rho_i - \rho_e)}$$

where the discharge coefficient C_d is a function of the window characteristics. Here it was found to be 0.65 by Bot (1983) for the greenhouse roof opening and was used again by Boulard and Baille (1995) for the greenhouse continuous roof vents. The outgoing ventilation flux per unit length of the window through the upper part is:

$$v_{,1} = \int_0^{h_1} v(z) dz \tag{3}$$

and the incoming ventilation flux per unit length through the lower part is:

$$v_{,2} = \int_{-h_2}^0 v(z) dz \tag{4}$$

Due to the continuity equation:

$$v_{,1} + v_{,2} = 0 \tag{5}$$

Combination of the equations (2) – (5) yields:

$$h_1 = h_2 = \frac{h}{2} \tag{6}$$

This means that the NPL of a single opening is at mid-height. Here the height h of the roof front aperture is a function of the opening angle according to **figure 2**:

$$h = H_0 [\sin \alpha - \sin(\alpha - \beta)] \quad (7)$$

Therefore, from equations (2), (3), (6) and (7), the ventilation flux per unit length can be written:

$$v = \frac{m}{3\sqrt{2}} H_0^{3/2} [\sin \alpha - \sin(\alpha - \beta)]^{3/2} \quad (8)$$

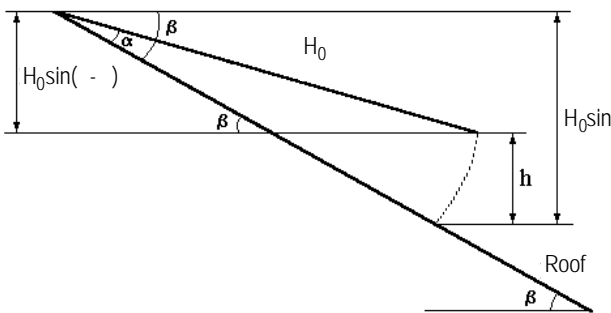


Figure 2. Vertical height of the front aperture of the roof opening — *Hauteur verticale de l'ouverture de l'ouvrant en toiture.*

The ventilation flux as a function of roof opening angle was shown in **figure 3** when the temperature difference between the interior and exterior air was 5K, 10K or 15K, respectively, with 273.15K or 283.15K as the exterior air temperature. We could see that the ventilation flux increased with the opening angle and the temperature difference T , but the relationship with both of them was non-linear. The ventilation flux at the exterior air temperature 273.15K was a little larger than that at 283.15K. This difference only reached $0.0001 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ for the extreme conditions ($\alpha = 40^\circ$, $T = 15\text{K}$). The absolute value of the air temperature had a very small effect on the ventilation flux and could thus be neglected. Besides, for increasing opening angles, the enhancement of the ventilation flux will reduce the temperature difference and the interaction between the two processes will give an effective flux lower than the calculated one for the case when the interior air temperature is maintained constant.

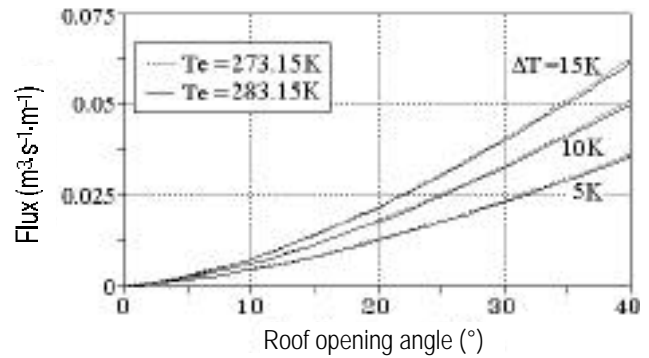


Figure 3. Ventilation flux due to the temperature effect as a function of the opening angle for the single roof window — *Flux de ventilation sous l'effet de température en fonction de l'angle d'ouverture du seul ouvrant de toiture.*

Wind effect

The wind action on the greenhouses appeared as a pressure distribution around them: a positive wind pressure resulting in an inflow of air and a negative one resulting in an outflow of air. The ventilation flux (half in, half out) per unit length due to the wind effect in a single opening can be written as:

$$v = C_d \frac{2}{L_0}^{1/2} \frac{A_w}{L_0} P_w^{1/2} \quad (9)$$

with the wind pressure:

$$P_w = C_p \frac{1}{2} u^2 \quad (10)$$

where the surface wind pressure loss coefficient C_p was given a value of -0.3 for the roof window of a greenhouse as proposed by De Jong (1990) and $C_d = 0.65$ as in equation (2). The front aperture area of the roof window was calculated by means of equation (7):

$$A_w = L_0 H_0 [\sin \alpha - \sin(\alpha - \beta)] \quad (11)$$

It was shown by **figure 4** that the ventilation flux due to the wind effect appeared to be proportional to the roof opening angle and increased, according to equations (9) and (10), linearly with the wind speed.

Combined wind and temperature effects

The above discussion of the wind and temperature effects on the ventilation was carried out separately and the isolated effects on the ventilation were fairly well understood. In fact, the air exchange was usually due to the combined wind and temperature effects. In order to solve this problem, an iterative method (Kozai,

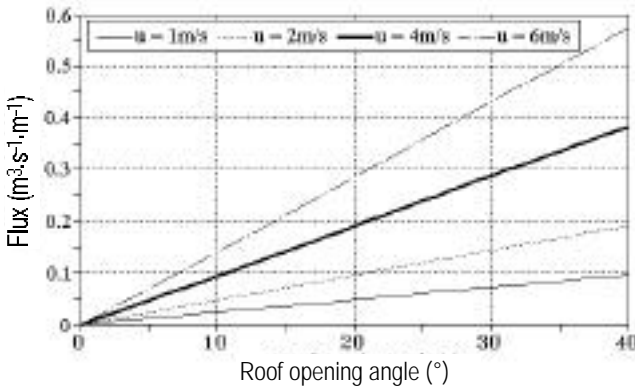


Figure 4. Ventilation flux due to the wind effect as a function of the roof opening angle for the single roof window — *Flux de ventilation sous l'effet du vent en fonction de l'angle d'ouverture du seul ouvrant de toiture.*

Sase, 1978; Vandaele, Wouters, 1994) had been often used to obtain the total internal pressure giving rise to the actual total pressure difference across the opening. To avoid the use of low efficient iterative procedures several simple methods of superposing the temperature and wind effects had been proposed as follows.

Method 1 (M1) (Boulard, Baille, 1995). The ventilation flux can be integrated over the half front aperture area according to the sum of thermal and wind pressure:

$$P = P_T + P_W = \frac{T}{T_e} g z + C_p \frac{1}{2} u^2 \quad (12)$$

since

$$v = C_d \int_0^{h/2} \sqrt{\frac{2}{T_e}} P^{1/2} dz \quad (13)$$

then

$$v = \frac{C_d T_e}{3g T} \frac{g T}{T_e} h + C_p u^2 \quad - (C_p u^2)^{3/2} \quad (14)$$

Method 2 (M2) (Walker, Wilson, 1993). The simplest method of combining v_{T} and v_{W} was to add equations (8) and (9):

$$v = v_{T} + v_{W} = \frac{m}{3\sqrt{2}} H_0^{3/2} [\sin - \sin (-)]^{3/2} + \frac{1}{2} C_d \frac{A_w}{L_0} C_p^{1/2} u \quad (15)$$

This method will produce large errors when the temperature and wind effects have the same order of magnitude.

Method 3 (M3) (Sherman, Grimsud, 1980; ASHRAE, 1985; De Jong, 1990). A more elaborated method was to consider the square root of the sum of the quadratic fluxes:

$$v = \sqrt{v_{T}^2 + v_{W}^2} \quad (16)$$

This method was experimentally validated by De Jong (1990) and it was largely used in the practice as recommended by the ASHRAE (1985).

Method 4 (M4) (Walker, Wilson, 1993). As an improvement of the preceding method, a parametric interaction term between the two fluxes was added:

$$v = \sqrt{v_{T}^2 + v_{W}^2 + B_1 v_{T} v_{W}} \quad (17)$$

Method 3 (quadratic superposition) sometimes was found to overestimate the combined ventilation flux, especially when the temperature and wind effects were comparable. However, when one or the other dominates the error was reduced. To account for this interaction an interference term could be introduced to act as a simple first order internal pressure shift correction. The coefficient B_1 was fitted by experiments and had been found to be -0.33 by Walker and Wilson (1993) for building leakages.

Results. The ventilation flux increased almost linearly with opening angle when the temperature difference between the interior and exterior air remained constant (at 15K). The results (**Figure 5**) showed that there were three equivalent methods for combining stack and wind effects at any wind speed. The estimations by Method 1 (M1) and Method 3 (M3) were practically identical at any wind speed and for the different roof opening angles. Method 2 (M2) always was above the latter and the overestimation increased with the opening angle. The flux obtained by Method 4 (M4) was a little below that of M1 and M3. It implied that the introduced interaction term in Method 4 with the coefficient B_1 for building leakages was also suitable for the roof opening of greenhouses. The three non-linear methods were physically more realistic and seemed to be equivalent for combining independent wind and temperature effect flows to estimate their combined effects. For the present study, the Method 3 was chosen because this method was validated by the experiments in the greenhouse roof opening (De Jong, 1990). Therefore, the linear addition of the fluxes

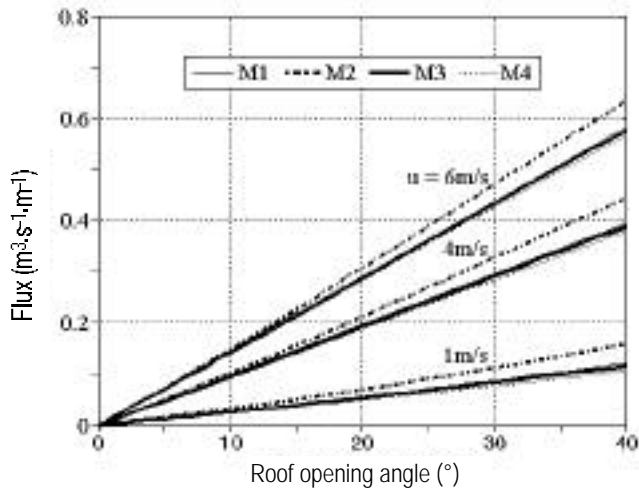


Figure 5. Comparison of the ventilation fluxes obtained by 4 different methods for different wind speeds at $T=15K$ as a function of the roof opening angle — *Comparaison des flux de ventilation obtenus par différentes méthodes pour différentes vitesses du vent, avec $T=15K$, en fonction de l'angle d'ouverture de l'ouvrant de toiture.*

(M2) was physically incorrect and produced the greatest error (De Jong, 1990; Walker, Wilson, 1993).

GREENHOUSE WITH ROOF AND SIDE OPENINGS

Temperature effect

In most Asian developing countries, such as in China, the single span greenhouses with roof and side wall openings were widely used. In this case, the ventilation due to temperature effect will be more effective because of a vertical distance D between the roof window and the side wall one (Figure 6). The side wall window was assumed to be controlled by its opening angle α' . When $\alpha' = 90^\circ$, the aperture was

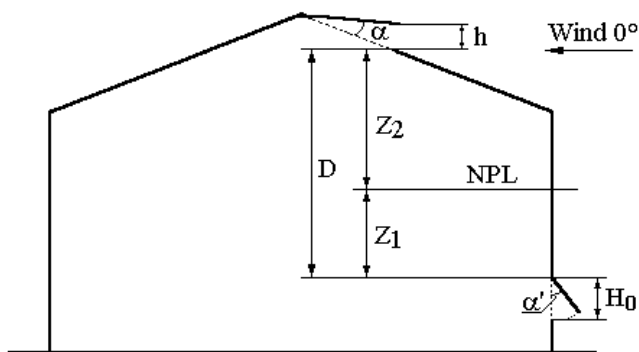


Figure 6. Geometry of the openings on the roof and the side wall — *Géométrie des ouvrants de toiture et de paroi latérale.*

equivalent to a sliding window which commonly appeared in greenhouses. If the width of the side wall window was exactly the same as those of the roof window, the ventilation fluxes through the front apertures of the roof opening and the side wall opening could be written according to equation (8):

$$v_{,roof} = \frac{2m}{3} \left\{ \left[Z_1 + H_0 (\sin \alpha - \sin(\alpha - \beta)) \right]^{3/2} - Z_2^{3/2} \right\} \quad (18)$$

$$v_{,side} = -\frac{2m}{3} \left\{ (Z_1 + H_0)^{3/2} - (Z_1 + H_0 \cos \alpha')^{3/2} \right\} \quad (19)$$

According to the continuity equation, the position of the neutral pressure level was a function of D , α and α' for fixed $T (= 15K)$ and $T_e (= 283.15K)$. Therefore, the ventilation flux of the greenhouse varied with them too. Firstly, we investigated the ventilation flux variation with distance D and roof opening angle α at a fixed opening angle $\alpha' = 45^\circ$ of the side wall opening. Figure 7 showed that the ventilation flux increased with the roof opening angle, but slowly. The vertical distance D was very important for the chimney effect. For a maximum opening angle, the ventilation flux for $D = 4H_0, 3H_0, 2H_0$ and $H_0 (= 0.785m)$ was about 4.59, 4.12, 3.59 and 2.96 times that of the greenhouse with the sole roof window. In this case, the neutral pressure level remained located between the two openings, that is, the air flow was outgoing from the roof window and incoming through the side wall one. The NPL could only be situated at an opening level if the two openings were of highly unequal size, which was not a practical case.

The ventilation flux through the side wall opening was shown in figure 8 in which the front aperture was

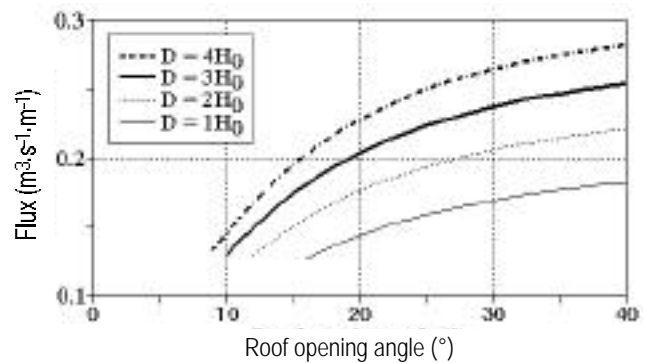


Figure 7. Temperature effect induced ventilation flux through combined roof and side wall openings as a function of α and D — *Flux de ventilation sous l'effet de température à travers les ouvrants de toiture et de paroi latérale en fonction de α et D .*

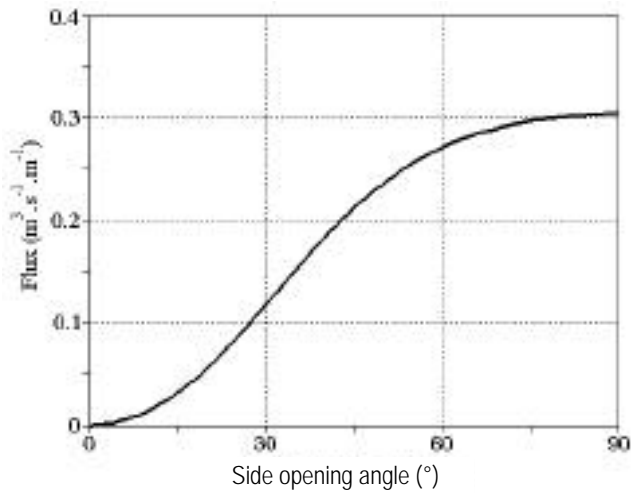


Figure 8. Temperature effect induced ventilation flux as a function of side opening angle at $T=15K$, $\theta=22^\circ$ and $D=3H_0$ — Flux de ventilation sous l'effet de température en fonction de l'angle d'ouverture de l'ouvrant sur la paroi verticale avec $T=15K$, $\theta=22^\circ$ et $D=3H_0$.

only used for air exchange. We investigated the ventilation flux variation with the side opening angle while the temperature difference, roof opening angle and distance between the two windows were fixed at $15K$, 22° and $3H_0$, respectively. It was observed that the ventilation flux increased with the side opening angle. Especially when the side opening angle was between 20° and 50° , the flux increased almost linearly.

The ventilation flux due to temperature effect was proportional to $T^{1/2}$ and to $T_e^{-1/2}$ according to equations (2) and (8). On the other hand, the first effect was important and the second one could be neglected based on **figure 3**.

Combined wind and temperature effects

When the external wind speed increased, the wind pressure contribution to the ventilation became important. Hence, the combination of both temperature and wind effects had to be determined for the various situations which included different wind directions and the opening angles of the two windows. As usual, the computation of the ventilation fluxes induced by the two effects through the roof and side wall openings was carried out by the use of the pressure distribution method. This method gave the ventilation flux based on the continuity equation and Bernoulli's theorem if the wind pressure and buoyancy force around the openings were known.

The temperature effect was maintained with the condition: $T=15K$ and $D=3H_0$. The wind effect ($u = 3 \text{ m}\cdot\text{s}^{-1}$ at roof level) on the greenhouse created a pressure field around the windows whose characteristic coefficients were taken from the technical data of

Kozai and Sase (1978) for windward (0°) and lee-side (180°) windows (**Table 1**).

Table 1. The surface wind pressure loss coefficient through the windows — Coefficient de perte de pression du vent à travers les ouvrants.

Wind direction	Roof window	Side wall window
0°	-0.3	0.4
180°	-0.7	-0.6

The combined ventilation flux was obtained for the two opposite wind directions as a function of the roof opening angle, with 45° of side wall opening angle (**Figure 9**). The flux through lee-side wind was larger than that for windward one and the difference between them increased with roof opening angle.

The values of the ventilation flux in **figure 9** (combined effect) and in **figure 7** (temperature effect only) had the same magnitude. In this two openings case, the temperature effect remained important even when the external wind speed reached $4 \text{ m}\cdot\text{s}^{-1}$ while it was negligible as soon as $u = 1.5 \text{ m}\cdot\text{s}^{-1}$ for the single roof opening case.

The combined ventilation flux as a function of the side opening angle was shown in **figure 10** with 22° roof opening angle under windward orientation. This flux increased with the side opening angle and the curve type was similar to that of **figure 8**. When the side opening was closed, the combined ventilation

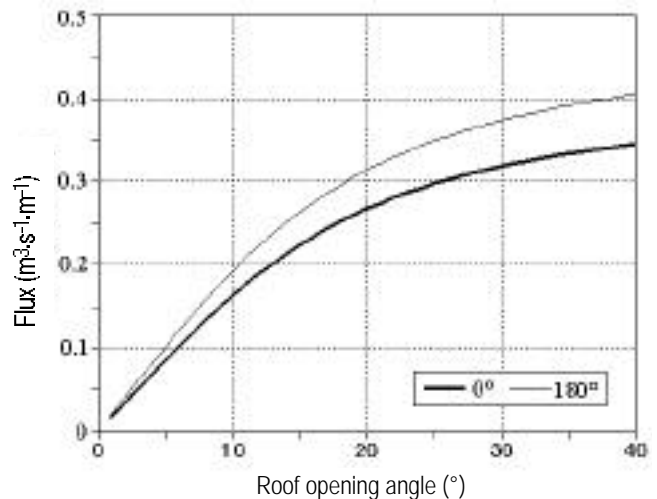


Figure 9. Combined temperature and wind effects induced ventilation flux as a function of the roof opening angle for leeside (180°) and windward (0°) winds — Flux de ventilation combiné sous l'effet du vent et de la température en fonction de l'angle d'ouverture de l'ouvrant de toiture sous le vent (180°) et face au vent (0°).

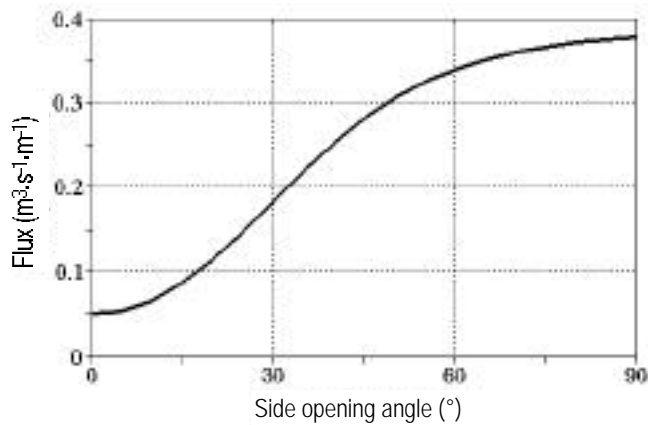


Figure 10. Combined wind and temperature effects induced ventilation flux as a function of the side opening angle — *Flux de ventilation combiné sous l'effet du vent et de la température en fonction de l'angle d'ouverture de paroi latérale.*

flux was not zero as was explained in previous section since the greenhouse was then reduced to the single roof opening case.

CONCLUSIONS

Natural ventilation in greenhouses was induced by both temperature and wind effects. The simple case of a greenhouse with a single sided longitudinal roof opening allowed us to perform the exact theoretical calculation of the natural ventilation flux. It was helpful to understand the ventilation mechanism under different greenhouse operating conditions based on the mass conservation.

The ventilation flux of a single span greenhouse with a roof window increased with the square root of the temperature difference and linearly with the external wind speed. The wind effect was largely dominant when its speed was larger than about $1.5 \text{ m}\cdot\text{s}^{-1}$. It was a simple and good choice for estimating the total airflow caused by combined wind and temperature effects to use the quadratic superposition. However, the temperature effect was very important when side wall openings were installed and the external wind speed was lower than $4 \text{ m}\cdot\text{s}^{-1}$. The combined flux increased with both the roof and side opening angles. This flux through lee-side winds was larger than that for windward side ones. The difference between them increased with roof opening angle. It seemed that the wind effect through lee-side opening was reinforced by the temperature effect in this case.

LIST OF SYMBOLS

A_w	window front aperture area, [m^2]
B_1	coefficient, [-]
C_d	discharge coefficient, [-]
C_p	surface pressure coefficient, [-]
D	vertical distance between roof and side windows, [m]
g	gravity acceleration, [$9.81 \text{ m}\cdot\text{s}^{-2}$]
h	height of the window aperture, [m]
h_1	height above the NPL of the window aperture, [m]
h_2	height below the NPL of the window aperture, [m]
H_0	window width, [m]
L_0	window length, [m]
T_e	exterior air temperature, [K]
T_i	interior air temperature, [K]
u	wind speed, [$\text{m}\cdot\text{s}^{-1}$]
$v(z)$	velocity in the opening at distance z , [$\text{m}\cdot\text{s}^{-1}$]
z	distance from the NPL, [m]
Z_1	distance between the NPL and the side window, [m]
Z_2	distance between the NPL and the roof window, [m]
α	opening angle of the roof window, [$^\circ$]
β	opening angle of the side window, [$^\circ$]
γ	roof slope of the greenhouse, [$^\circ$]
P	pressure difference, [Pa]
P_T	pressure difference due to temperature effect, [Pa]
$P_{T(z)}$	pressure difference due to temperature effect at height z , [Pa]
P_w	wind pressure relative to the undisturbed flow, [Pa]
T	temperature difference, [K]

	mean air density in the opening, [kg·m ⁻³]
e	exterior air density, [kg·m ⁻³]
i	interior air density, [kg·m ⁻³]
v	ventilation flux, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,1}	ventilation flux through the upper part of the window, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,2}	ventilation flux through the lower part of the window, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,roof}	ventilation flux through the roof ventilator, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,side}	ventilation flux through the side ventilator, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,T}	ventilation flux due to temperature effect, [m ³ ·s ⁻¹ ·m ⁻¹]
v _{,W}	ventilation flux due to wind effect, [m ³ ·s ⁻¹ ·m ⁻¹]

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