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NATURAL VENTILATION PERFORMANCE OF A GREENHOUSE TUNNEL IN SOUTH TUNISIA

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Abstract: After recalling the physical model basis of the natural ventilation, we examine the ventilation performance of a greenhouse tunnel equipped with either roof or door openings or both roof and door openings. Altogether four different ventilation configurations are analyzed. Neural networks of ventilation rate were first developed to select relevant parameters influencing the ventilation performances. It confirms that the surface area of the vent opening and wind speed together explain the largest part of the variance of air exchange rate measurements. Ventilation performance is then analyzed against physical models derived from Bernoulli's theorem. The effects of vent-openings, their positions and types are considered together with different models combining the two major forces for natural ventilation wind and stack forces.

INTRODUCTION

The use of greenhouse tunnel is rapidly expanding in the south of Tunisia where geothermal water is widely used for greenhouse heating and crop irrigation. In this context, ventilation performance is a major factor in production, conditioning both climates controls and yields quality over much of the year. Though, in contrast to situation pertaining to the venlo type shelter widely used in Northern Europe (Bot[1], de Jong, Fernandez and Bailey), no investigations of the performance of tunnel greenhouse in saharian climates have been undertaken. Some progress has been recently made: tunnel and low tunnel ventilation have been analyzed by means of statistical approaches (Feuilloley et al., Kittas et al., Feuilloley et al.), and multispan plasti-chouses using physical modeling based on Bernoulli's equation (Boulard, Boulard and Draoui, Papadakis et al.). Performance criteria based on these very different approaches are difficult to compare and a common approach more clearly based on physical concepts is required to examine greenhouse performance with respect to their engineering design.

The main driving forces for natural ventilation are firstly, the wind forces and secondly, the buoyancy forces driven by the difference in air temperature between the interior and exterior. Wind forces alone largely explain ventilation flows of the Venlo type greenhouse (Bot), whereas the combined influence of wind and buoyancy forces are considered important for the Mediterranean greenhouses (Boulard).

Ventilation mechanisms are quite complex and remain poorly understood. Since neural network models (NN) are very flexible, they may be as an initial screening tool (Seginer et al.), employed preparatory to physical modeling. They allow marginally useful inputs to be identified and thus help in reducing the number of relevant variables implicated. Furthermore, differences between the degree of fit of the physical and neural network models are one measure of the physical understanding underlying the model (Seginer et al.).

In this paper, after first recalling the basic theoretical considerations concerning the ventilation mechanisms, we shall present the ventilation performances of a greenhouse tunnel type, ventilated with either roof vents opened door or both roof vents and opened door. All together four different ventilation systems will be considered and their performances analyzed using neural networks and physical models.

THEORY

The wind effect is considered to be the most important driving force for ventilation in greenhouses equipped with only roof vents (Bot, de Jong, Fernandez and Bailey, Boulard and Draoui, Kittas et al.) and also for greenhouses equipped with both roof and side vents (Boulard, Papadakis et al.). It has two components: a static one, linked to the wind pressure field over the greenhouse cover, and a turbulent one, linked to the wind turbulence along the opening (Boulard et al.). The static effect gives rise to a vertical and horizontal distribution of pressures, respectively between the side and roof vents, and between the upwind and downwind part of the same vent. In addition we must consider the 'chimney' effect linked to the vertical distribution of static pressures between inside and outside the greenhouse and giving rise to an air inflow in the lower part of the opening (or through a lower vent) and an outflow from the upper part (Bruce).

The ventilation airflow rate G (m^3s^{-1}) of a greenhouse equipped with only roof or side vents can be simulated with a good accuracy by a simple model combining these wind and chimney effects (Boulard and Baille):

$$G = S/2\ A[2g\ (DT/T)(H/2) + C_W U^2]^{0.5} \qquad (1)$$

where S (m^2) is the vent opening (the open cross-sectional area), DT is the difference between the inside and outside air temperatures, T (K) is the outside temperature, U (ms^{-1}) is the wind speed, g ($m\ s^{-2}$) is the gravitational constant and H (m) is the distance between the surfaces of air inflow and outflow (equal, for a vertical opening, to the half of the height of the opening). A is the dimensionless discharge coefficient and C_W the dimensionless overall wind effect coefficient which shall be calibrated *in-situ* by fitting the experimental data to the model.

For a greenhouse equipped with roof and side openings, the ventilation rate is giving by a similar expression where H is the vertical distance-separating roof and side vents (i.e. the height of the 'chimney ').

The ventilation flux of a greenhouse, equipped with both roof and side openings, can be described by an equation analogous to equation 1 (Boulard, Kittas et al.), where the 'chimney' effect depends on ε and the relative importance of the roof S_R and side S_S vent's surface, their sum $S_T = S_R + S_S$ and H, the vertical distance separating the roof and side vents:

$$G = (S_T/2)A[\ 2g\ \varepsilon^2\ (DT/T)\ (H/2) + C_w U^2]^{\ 0.5} \qquad (2)$$

with :

$$\varepsilon = 2\ \sqrt{2b}\ /\ (1+b)\ (1+b^2)^{0.5}$$

and

$$b = S_R\ /S_S$$

If either DT or H are small, the wind effect is much more important than the chimney effect which can be neglected, then:

$$G = (S/2)\ A\sqrt{C_w}\ U \qquad (3)$$

From G, we obtain N, the greenhouse air exchange rate (h^{-1}):

$$N = 3600\ (G/V) \qquad (4)$$

where V is the greenhouse volume. Combining equation (1) or (2) and (4), and considering $s=S/S_s$ the ratio of vents opening per ground area S_s and h the average height of the greenhouse $h = V/S_s$, equations (1) or (2) become (5) :

$$N = (3600/h)\ (s/2)\ A[2g\ (DT/T)\ (H/2) + Cw\ U^2]^{0.5} \tag{5}$$

or, after neglecting the chimney effect,

$$N = (3600/h)\ (s/2) A \sqrt{C_w}\ U \tag{6}$$

If N_O represents the onset of ventilation (or leakage) when s= 0 (or when U=0), we can slightly modify the relation (6) as follows:

$$N = (3600/h)(s/2)\ A \sqrt{C_w}\ U + N_O \tag{7}$$

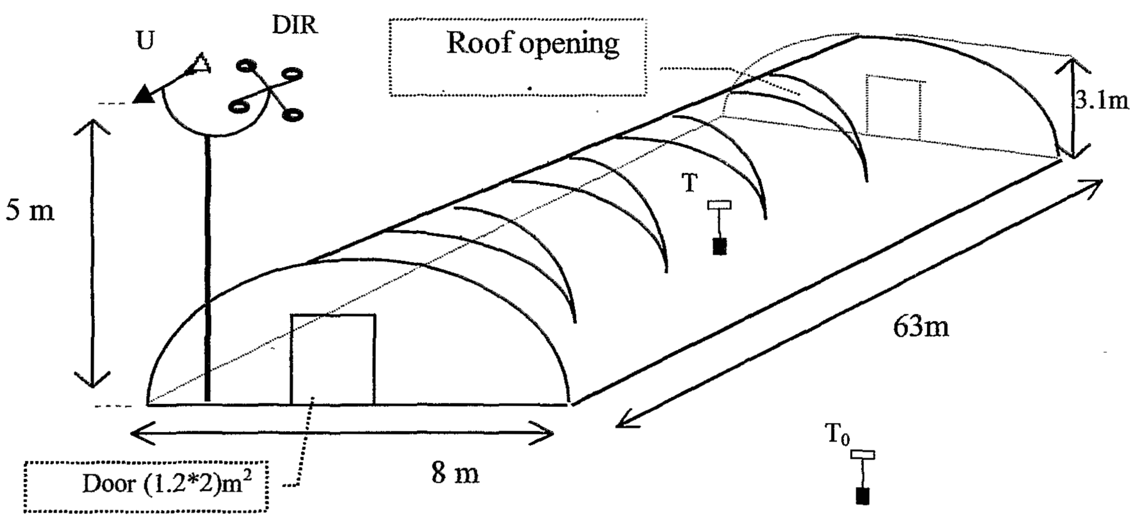

Figure 1. Scheme of the experimental greenhouse

EXPERIMENTAL

The main characteristics of the greenhouse and its aeration systems are shown in schematic form in figure 1 and summarized in table 1. The tunnel ground area was 504 m^2, with his maximal height was equal to 3.1 m and his average height (h) equal to 2.4m. This configuration is representative of the Tunisian shelters. The most of the measurements were performed in greenhouses occupied by a young tomato crop (third truss).

Table 1: Main design characteristics of the ventilation systems

Vents type	Measurement's number	Height of the vents (m)	Ratio of door /roof openings
Roof opening	18	0	750
Door opening	8	1	0
Roof and side opening	16	2.1	-
Closed greenhouse opening	6	2.1	1

Supporting measurements

Air exchange rate N measurements were performed using « N_20 » as the tracer gas with simultaneous recording of climatic variables and manual measurement of vent-opening area. The gas was sampled from eight different locations at a height of 2 m and equally distributed over the tunnel greenhouse as shown in figure 2. In all cases, after an initial « N_20 » release and stabilisation of the inside concentration, the decay in concentration rate C(t) was monitored and N deduced as follows

$$C(t) = C(t_O) \exp(-N (t-t_O)) \qquad (8)$$

where t_O is the initial time.

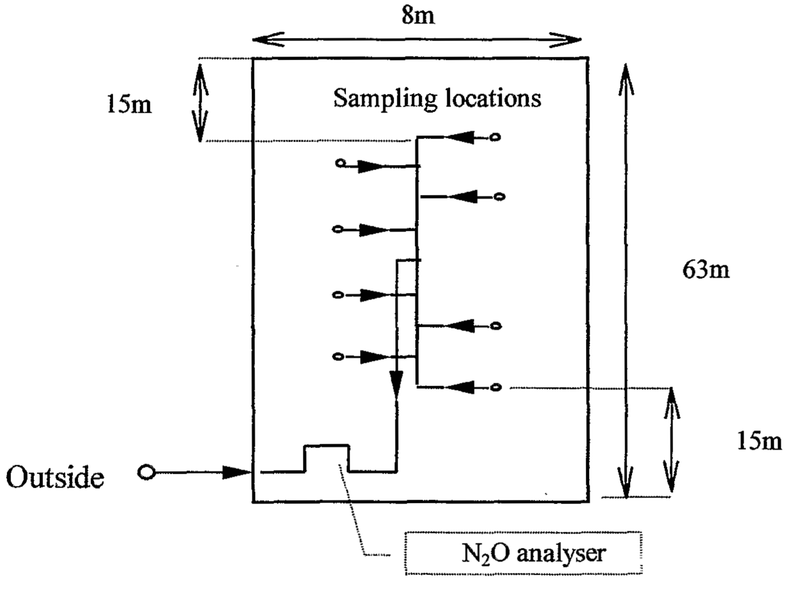

Figure 2. Scheme of the tracer gas measurements. The N_2O analyzer aspirates the air from 8 positions equally distributed over the greenhouse and located at a height of 2m.

Height of wind speed and wind direction measurement and the exposure of the cup anemometer are given in figure 1. During the air exchange rate measurements inside and outside air temperatures, wind speed and direction, and vent opening, were measured and averaged over each decay period (3 to 40 min). A summary of these averaged values is found in table 2.

Table 2: Average values of the climatic and design parameters of the ventilation system

	Number of measurements	s (m^2)	H (m)	N (h^{-1})	U (ms^{-1})	DT (°C)
Roof	18	0.031	0	11.3	2.65	3.96
Door	8	0.0096	1	3.66	2.2	4.1
roof and Door	16	0.046	2.1	17	2.78	4.22
closed greenhouse	6	0	-	1.89	1.67	3.63

Neural network model's program

The neural net models (Seginer et al., Dayhoff) were trained with a commercial program (Neuroshell ™, Ward System Group). The models had a feed-forward, three layers, input hidden and output architecture; and the input/output were the measured data. With as input, be variables which are supposed to explain the ventilation performances (s, H, DT, b, see equations 1 to 6); and as output the measured air exchange rate N. The training algorithm was back propagation and the number of hidden node was always set to be equal to twice the square root of the sum of input and output nodes (determined by the program default).

RESULTS

Neural network models of ventilation rates

As seen in section 2, a number of physical models have been developed and which differ from one another in the degree of refinement with which they consider the chimney and wind effect. It is therefore important to weigh the input information required for each particular model and NN models is a black box modeling which provides a useful tool for screening the importance of the inputs.

For this, we used a data file containing the 48 records of the greenhouse air exchange rate N as output and control variables (ratio of vent opening surface s, height of the 'chimney' H and the ratio of roof opening by door opening b); and the weather variables (U, DIR, wind speed and direction and DT: the difference of temperature between inside and outside) as inputs.

Table 3 summarizes the results of four different « NN » tests and allows us to weigh the respective importance of the different inputs. Test T1, using all inputs, results in a R^2 of 0.91, implying that other variables not considered in this model would be required to improve the model fit. It corresponds namely to the values of the model parameters (A and C_w), depending on interactions between wind and greenhouse and on greenhouse and vent design. Elimination, in T2, of the wind direction (DIR), did not seriously reduce the predictive power of the model, but the elimination of the inputs linked to the 'chimney' effect DT, b1 and H, in test T4, results in a strong reduction of the fit (R^2 = 0.70). Further elimination of U in test T5 resulted in drastic reductions in the goodness of the fit (R^2 = 0.29). This hierarchy of inputs, which clearly demonstrates the pre-eminence of the wind effect over the stack effect, confirms too that the 'chimney' effect is not negligible and that the air exchange rate is not very sensible to the wind direction.

Table 3 : Neural network models of the greenhouse ventilation. Weight of input variables and correlation coefficient (R^2) of the regression between measured and calculated (using the NN modelization). Networks T1 to T5 were trained with all the data (Door, roof, closed greenhouse, roof and side), all together 48 data records

	Test				
Inputs	**T1**	**T2**	**T3**	**T4**	**T5**
U	58.7	14.6	6.5	15.7	-
DT	45.1	11	4	-	4.3
DIR	9.7	-	-	-	-
s	104.2	40.1	13.1	27	29.5
b1	41.4	8.4	-	-	-
H	34	8.6	-	-	-
sum	283.1	82	23.6	42.7	33.8
R^2	0.91	0.89	0.74	0.70	0.29

Physical modeling

Linear dependence of N on U and s

In a first step, we have tested the dependence of N on the most relevant input parameters, U and s. Figure 3 illustrates the evolution of N versus (3600sU/2h) for the different ventilation systems. Independently of wind speed and vent opening, this presentation allows to estimate the ventilation performance of each system and thus to weigh its efficiency. Following relation (6), this latter is given by the slope, $A\sqrt{C_w}$, of N versus (3600sU/2h), a summary of the regression parameters with confidence intervals is given in table 4.

Table 4 : Recapitulative of the values and confidence intervals of the ventilation parameters $A\sqrt{C_w}$, N_0 when we consider a linear dependence of N on (3600sU/2h), (eq. 6) R^2: coefficient of correlation, n = number of records

Roof opening	Roof and Door opening	Door opening	closed tunnel
$A\sqrt{C_w} = 0.157 \pm 0.026$	$A\sqrt{C_w} = 0.13 \pm 0.03$	$A\sqrt{C_w} = 0.22 \pm 0.028$	$A\sqrt{C_w} = 0.18 \pm 0.032$
$N_0 = 4.7 \pm 1.5$	$N_0 = 8.9 \pm 2.4$	$N_0 = 1.2 \pm 0.46$	$N_0 = 0.1 \pm 0.017$
$R^2 = 0.69$, n=18	$R^2 = 0.73$, n=16	$R^2 = 0.87$, n=8	$R^2 = 0.73$, n=6

The leakage area s_0 for the closed greenhouse was identified using a slightly modified version of eq.6: $N = (3600/h)((s+s_0)/2)\ A\sqrt{C_w}\ U$ (9). The two parameters $A\sqrt{C_w}$ and $s_0\ A\sqrt{C_w}$ were identified by fitting the experimental data of closed greenhouse and roof opening together to the model of eq.9, using a non linear regression package (Marquardt's Algorithms, Marquardt[16]). The ratio of the two identified values gives s_0=0.0075. Table 4 shows that the wind related ventilation efficiency ($A\sqrt{C_w}$) of the roof opening (0.157 ± 0.026) is statically different of this of the door opening (0.22 ± 0.028), but the difference is not very important. Both values are in good agreement with other values already reported in the literature (Boulard et al. [12]) for a Richel type tunnel equipped with roof openings (0.15 ± 0.02), for a BN tunnel, (0.165 ± 0.01) and for a Filclair greenhouse (0.18 ± 0.01). We can remark too that the offset N_0 (4.7 ± 1.5) is not very different of the values already calculated for the Richel tunnel (4.9 ±1.8), the BN tunnel (8.6 ± 0.9) and the Filclair greenhouse (6.5 ± 1). Comparison of the parameters values of Table 4 shows that N_0, which takes implicitly into account the 'chimney' effect is maximum when booth roof and door are open, i.e. when the height of the 'chimney': H is maximal (see equation5).

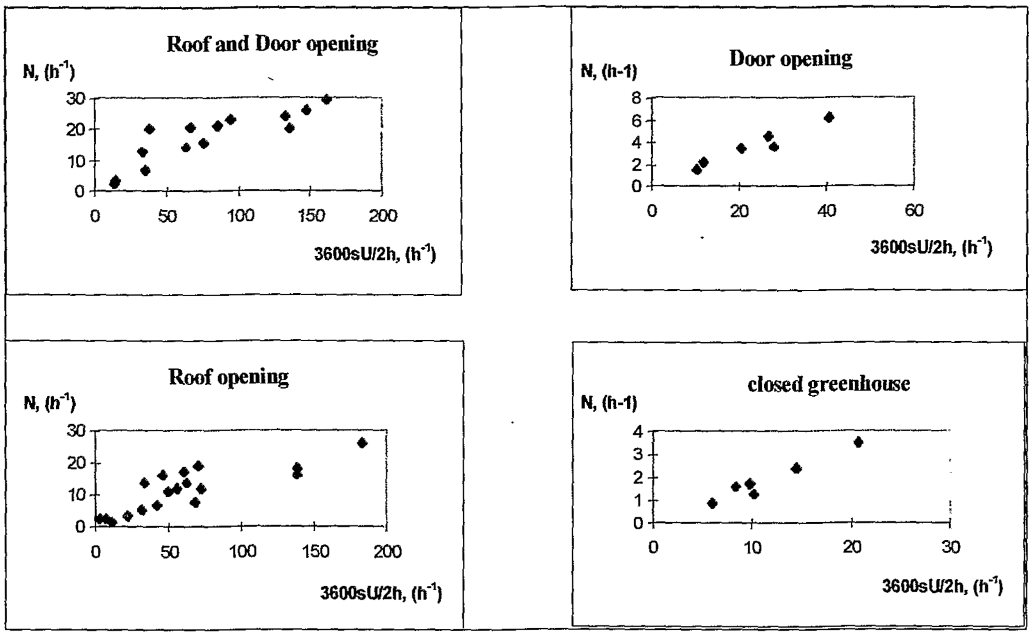

Figure 3. N Versus (3600sU/2h) for roof, door, roof and door openings in the closed greenhouse

Sensitivity of the model parameters to vents opening surfaces and wind velocity

The residuals of regression analysis of N versus (3600sU/2h), with respect to vent opening (s) have an aleatory distribution. This is in agreement with earlier analyses of Papadakis et al. and Seginer et al. for a multispan greenhouse and of Kittas at al. for a tunnel equipped with side openings: all of this studies have demonstrated a linear relationship between the vent opening and ventilation rate.

The decrease of the ventilation efficiency ($A\sqrt{C_w}$) with increasing N values is closely related with the increase of the wind speed (Table 5) as well for roof opening than for both roof and door openings. The evolution of (N) versus (3600sU/2h) demonstrates clearly (Fig.4) that the linear dependence of N on U, expressed by relation (7), is not entirely satisfactory. High wind speed gives rise to a decrease of the slope $A\sqrt{C_w}$ and to an artificial increase of N_0. The wind effect is no longer the main driving force of ventilation as wind speed tends to zero. We have then, as expressed by (eq.5) to consider the chimney effect which is no more negligible.

Table 5: Effect of wind velocity on the identified values of the ventilation parameters: $A\sqrt{C_w}$, N_0, R^2 = coefficient of correlation between measured and modelized values, n = number of data records.

Roof opening		*Door and Roof Opening*	
$U < 2\ ms^{-1}$	$4 > U \geq 2\ ms^{-1}$	$U < 2\ ms^{-1}$	$4 > U \geq 2\ ms^{-1}$
$A\sqrt{C_w} = 0.175$, N_0=3.8	$A\sqrt{C_w} = 0.147$, N_0=5.1	$A\sqrt{C_w}$ =0.15, N_0=6.9	$A\sqrt{C_w} = 0.09$, N_0=9.8
R^2=0.61, n= 8	R^2=0.54, n= 10	R^2 =0.75, n= 10	R^2=0.70, n=6

Combination of wind and stack effects

C_W and A were identified by fitting the experimental data to the model of equation 5 using a non linear regression package (Marquardt's Algorithm, Marquardt) and compared with A C_W values identified by means of the simplified model given by eq.6. Table 6 highlights the relative influences of the 'chimney' effects at low wind speed on $A\sqrt{C_w}$ value. If we consider the wind effect alone, we observe a dramatic decrease of $A\sqrt{C_w}$ with increasing wind speed, and particularly at low wind speeds. If the stack effect is not neglected, the decrease of $A\sqrt{C_w}$ with wind speed can still be identified but with a much smaller and non-statically significative extent. In summary, it seems that the influence of the wind velocity on the ventilation is preponderant over 2 ms^{-1} and that below this limit the 'chimney' effect (and DT between inside and outside) has to be considered.

Table 6: Influence of wind speed on the identified value (and confidence interval) of the parameter of 'wind related' ventilation efficiency: $A\sqrt{C_w}$, when we consider only the wind effect (relation 6) or a combination of both wind and chimney effect (relation 5). Case of door openings with door and roof openings

	$0<U<2\ m\ s^{-1}$	$2<U<4\ m\ s^{-1}$
Wind + chimney effects	0.185 ± 0.045 R^2= 0.86	0.169 ± 0.032 R^2= 0.81
Only wind effect	0.215 ± 0.025 R^2= 0.77	0.147 ± 0.055 R^2= 0.65
Number of measurements	14	10

DICUSSION AND CONCLUSION

Air exchange rate measurements performed in greenhouse tunnel type are presented and analyzed with reference to physical and describing the combination of the two major driving forces of ventilation: wind and stack effects. Neural networks of ventilation rates allowed us to first select the relevant parameters involved in physical modeling and the following hierarchy of importance of the inputs (with descending order) was found: s, U, DT, H, b, DIR. Vent-opening and wind speed together explained more than 50% of the total variance of the air exchange rate measurements whereas using all the inputs of the physical model based on Bernoulli's theorem (s, U, DT, H, b, DIR) explained only a further 30%. This indicates that other factors, not considered in the models derived from Bernoulli's theorem need to be considered.

The physical analysis shows that the wind effect is the major cause of the air exchange between inside and outside for the greenhouse and vent systems considered in this paper. The 'chimney' effect, linked to the DT between inside and outside, is only important at low wind speed ($U<2m\ s^{-1}$) and when roof and door vents are open together, giving rise to a tall 'chimney.'

Some general properties were also established: the linear dependence of N to U and s, suggested by the simplified physical model (6 and 7), is only partially supported by the data and a decrease with increasing wind speed, of the wind related ventilation efficiency is observed. Combining both wind and stack effects did not improve significantly the predictive power of the model for the roof vents, but when both Door and Roof vents are open together (the stack effect is maximized by the effective height of the 'chimney') the model performance is improved by combination of the two driving forces.

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Notations

A	Discharge coefficient
C_W	Wind effect coefficient
C(t)	Tracer gas concentration at time t (ppm)
S	Vent's opening surface (m^2)
s	Relative vent's opening surface per ground area
H	Vertical distance separating the surfaces of air inflow and outflow (buoyancy forces) (m)
h	Height of the greenhouse (m)
G	Volumic flow rate (m^3 s^{-1})
N	Hourly air exchange rate (h^{-1})
N_0	Hourly air exchange rate for s = 0 (h^{-1})
DT	Difference of temperature between inside and outside (°C)
U	Wind speed (m s^{-1})
V	Greenhouse volume (m^3)
g	Gravity constant (ms^{-2})

Subscripts

S side	T total
R roof	s soil