Greenhouse aeration and climate optimization based on CFD studies

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Abstract

Based on new opportunities to use numerical computation of air movements and climate within greenhouses by means of the so called computation fluid dynamic's softwares (CFD), a study was undertaken for improving the greenhouse design and ventilation equipments. Three main domains have been explored, i) the consequences of deploying greenhouse insect screens on inside climate; ii) the optimisation of ventilation with the existing ventilation facilities, iii) the greenhouse ventilation and climate improvement by means of simple design modifications such as the increase of the greenhouse height or a modification of the shape of the arch.

It was shown that screening vent openings with anti Bemisia nets divides by a factor 2 air exchange rate and air speed inside the greenhouse and consequently induces a doubling of both the air humidity and temperature rises with respect to outside. It was also demonstrated that structural design elements such as the height of the greenhouse and the shape of the arch strongly influence the greenhouse ventilation and climate performances.

The most efficient vents orientation was also studied and it was shown that orientating the vents parallel to the wind direction was the most efficient strategy, but which also generates strong climate heterogeneity. In case of a wind direction perpendicular to the gutters line, the windward orientation is also more efficient than the leeward one.

1. Introduction and objectives

Thanks to the use of Computer Fluids Dynamics (CFD) models, recent and important progress were recently observed for the modelling of the greenhouse distributed climate and particularly the climate at crop level. This was mainly achieved by including the effects of the dynamic action of the crop on the flow and the subsequent heat and mass exchanges (Boulard and Wang, 2002).

Most of the existing greenhouse types were tested: plastic tunnels (Roy and Boulard, 2004); multispan plastichouses (Mistriotis *et al.*, 1997a; Mistriotis *et al.*, 1997b); large scale Canarian type plastic houses (Fatnassi *et al.*, 2003; Campen and Bot, 2003; Molina *et al.*, 2004); Venlo type glasshouses (Reichrath and Davis, 2002), or equipped with continuous roof vents (Haxaire, 1999; Ould Kahoua *et al*., 2004; Lee and Short, 2000).

The progress in the field of the characterization of inside convection and distributed climate within real scale greenhouse were also essential as illustrated by the studies of Haxaire (1999) and Shilo *et al*. (2004) who have mapped the convective and climate patterns in commercial multispan plastic houses or in greenhouse tunnels (Boulard *et al.,* 2000) using sonic anemometry.

Combining studies on numerical modelling and climate characterisation has allowed for the validation of these numerical greenhouse crop models both for multispan plastichouses (Haxaire, 1999), large scale Canarian type plastic houses (Fatnassi *et al*., 2003) or single span greenhouses (Bartzanas *et al*., 2004). Likewise, recent studies of Boulard *et al*. (2004) and Ould Kahoua *et al.* (2006) demonstrate that it was possible to validate the whole ventilation performances of a greenhouse by comparing the decay rates of real and virtual tracer gas within the greenhouse. The relatively good fit which was generally observed between measured and simulated values of the convective and climate fields or ventilation performances has given confidence in the use of such numerical for further sensitivity studies.

The recent intrusion in south Europe of emerging insect pests such as the white fly *Bemisia tabaci*, one of the world's most important pest species transmitting many viruses, has made necessary physical protection of greenhouse crops using insect proof nets. However the pressure drops induced on the air movements reduce the greenhouse air exchange rates and increase dramatically inside air temperature and humidity.

Based on the CFD capabilities, a study was undertaken with the greenhouse manufacturer Filclair SA, to exploit the CFD capabilities in order to try improving the greenhouse ventilation performances by simulating the consequences of using insect proof nets on the openings, together with the variations of the structural elements of the greenhouse: vents position, surface and orientation, shape of the arches or height of the greenhouse.

2. Materials and methods

2.1. The numerical model

With regard to numerical simulations, some authors have been used commercial or self-developed CFD codes to perform simulations for various greenhouse configurations. From these studies, summarized in a review paper by Boulard *et al.* (2002), it can be deduced that the use of a 3D model and the taking into account of the inner vegetation are two essential points for the consistency of the numerical results.

In this study, we present the results of a model that combines different scales of a 3D model (the greenhouse an its direct environment; the inner domain of the greenhouse) and that takes into account an active crop by modeling the crop as a porous medium and determining the heat and water vapour exchanges at crop level (Boulard and Wang, 2002, Roy and Boulard, 2004). This model has been adapted to the CFD2000® software (Haxaire, 1999; Fatnassi *et al.*, 2003) to determine the airflow, temperature and humidity patterns in a greenhouse, then to analyze the influence of both boundary conditions (wind speed and direction) and greenhouse and vent's design on its climate performances.

2.2. The greenhouses and their boundary conditions

The greenhouse

This study is principally based on the modelling of a eight spans arch type plastic house (Fig. 1): 8×9.6 m width, 80 m length and 5.93 m high at the roof top (4 m high at gutters height). Ventilation is performed by means of 1.5 m high continuous vent openings located at gutters height (Fig. 1). However, several variations with respect to this base type will also be examined in this study: variation of the arches shape, height of the greenhouse, presence or lack of insect proof nets.

This greenhouse is occupied by a virtual 2m high rose crop with a leaf area index of 3 m^2 of leaves/ m^2 of soil. Both the dynamic effect of the crop cover on air flow and the latent and sensible heat exchanges with ambient air were also considered and modeled in interactions with the air flow.

The boundary conditions

Climate conditions characteristics of an average summer day in Mediterranean conditions have been selected (NB, the temperature scale is given in Kelvin, 273K=0°C):
- Outside temperature: 300 K (27°C);
- Outside humidity: 50 % RH;
- Outside global radiation: 690 W/m^2,
- Logarithmic wind speed profile with a 2.5 m/s speed at 5 m high.

2.3. The different simulations

The consequences of several variations of the greenhouse and vents design or orientation have been investigated and we shall only focus on the effects of six principal modifications:

The effects of an anti Bemisia insect proof net in the openings for leeward ventilation;
The effects of the vent opening orientation, windward, leeward, parallel to the wind direction;
The effects of the suppression of one vent opening line on two (preservation of one opening line for 2 spans);
The effects of the greenhouse height (5m, 4m and 3m at gutter level);
The effects of the shape of the greenhouse arch.

3 Results

3.1. The numerical simulation outputs

For a leeward orientation of the vents (positioned at gutter height), examples of the different dynamics, temperature and humidity fields along a vertical cross section of the whole plastic house are shown in Figs. 2, 3 and 4. The general circulation of air is highlighted in Fig.2, with cold air entries through the 3 first vents (light blue arrows: 301K), both air entries (light blue arrows: 301K) and exits (green arrows: 303K) in the two following ones, and only air exits (green, 303K; and yellow arrows, 306K) in the three last vents, and particularly in the last one where air exits with the highest flow rate and the highest temperature. One can also remark the undulating air circulation within the greenhouse, under the influences of both the air entries and exits through the vents and the arch shape of the roof. As a consequence of this circulation, the general air current is periodically impeded by the crop cover. Numerical values of the climate fields can be deduced (Fig. 3) along a vertical cross section at crop height (0.5m) and used for analysis or comparisons with other configurations. With in view a simplification of the analysis, we shall use this representation to later compare the climate consequences of different designs. On the air humidity exchange point of view, Fig. 4 shows clearly that, in presence of a crop cover in the greenhouse, the periodic temperature and humidity fields are quite comparable, but with clearly an increase of air humidity from the windward to the leeward part of the greenhouse.

The horizontal cross section of air humidity at 0.5 m high in the crop cover (Fig. 5) confirms this progressive humidification of air from windward to the leeward part of the greenhouse, together with a reduction of the periodic character of the distribution of the humidity field (the phenomenon is similar for the temperature field) on the lateral sides of the greenhouse.

For better understanding of air circulation and temperature and humidity patterns, one can also zoom on critical parts of the greenhouse as it is the case for the vertical cross sections of the thermal and dynamic fields in the 1st, 4th and 8th spans of the greenhouse (Figs 5, a, b, c). One can see that outside air predominantly enters in the greenhouse at counter current (with respect to wind direction) through the first vent, then turns and penetrates deeply in the crop cover in the first span (Fig. 5a).

Feed by the air entering through the vents and the arch shape of the roof, it gives rise to a periodic circulation of the air from the windward to the leeward parts of the greenhouse (Fig.

5b). One can also remark that warm air exits through the upper part of the vent and cold air penetrates through the lower one.
Fig.5b also clearly demonstrates that warm air (yellow arrows) goes out from the greenhouse predominantly through the last leeward vent and that the two previous vents are also air exits (yellow arrows) but with a quite smaller rate than the last one.

3.2 Effect of an anti Bemisia net

We have tested the effect of anti bemisia insect proof nets (Figs 7) on the air flow and climate patterns for the same boundary conditions as the previous ones.
Comparing the air temperature and speed patterns in the greenhouses equipped (Fig 7) or without nets (Fig 2), one can remark a dramatic decrease of the air speed which is divided by between 2 and 4 in the netted greenhouse. Consequently, air temperature rises in the greenhouse with the nets of more than 2K (Fig. 7 and Fig. 8 a) and air humidity of more than 7% RH (Fig. 8b).

3.3. Effect of the greenhouse height

The general increase of greenhouse height and volume all over the world and particularly in hot regions these twenty last years let us suppose that this parameter has a strong action on the fixation of inside climate. To investigate more thoroughly this point, we have simulated the inside climate in two similar multispan greenhouses (base type presented earlier) differing only by their height, i.e respectively 3m, 4m, 5m at the gutter level, in similar climate conditions. Fig 9a recapitulates the corresponding inside air temperature profiles (at 0.5 m high) along the 8 spans of the greenhouses. One can immediately remark a clear decrease of inside air temperature while increasing greenhouse height. On average (Fig; 9b) inside air temperature decreases of about 2K when passing from 3 to 4m high, but less than a K when passing from 4 to 5m high. The effect of greenhouse height increase on inside air temperature decrease is clearly asymptotic. As the cost of the elevation of the greenhouse is rather important, we can conclude that if we consider an economic optimal, it is not always necessary to try to rise too much the greenhouse.

3.4. Effects of lowering the height of the arch

We have seen in the § 3.1 that the shape of the arch largely explains the undulatory profile of air circulation within the greenhouse (Fig.2), which directly influence the air temperature and humidity patterns (Figs 2 & 4). In this section we have tried to investigate the consequences of a modification of the shape of the arch and we have simulated the inside climate patterns when lowering the height of the arch from 1.93m for the base type to 1.30m. Inside air circulation and temperature patterns with the 1.30m high arch are presented in Fig 10, and can be compared with those obtained with the standard one (Fig 2). A clear modification of inside air circuit (comparison of Figs 11 & 3) can be stated with the lower arch height and one can remark a straighter air circulation which favours the air exchange and induces a significant decrease of inside air temperature (-1.5K).

3.4. Effects of reducing the number of vent openings

Previous analysis of air exchanges through the roof vents has shown that the vents have not all the same efficiency and that some ones, particularly the first and the last ones were more efficient. Considering also that the cost of the vents represents a large part of the greenhouse cost (≈ ¼) we have been laid to examine if suppressing one line of roof vents on two could seriously affect the inside climate. The results of this simulation are given in Fig 12 for the vertical section of the dynamic and temperature fields in the greenhouse and in Fig 13 for the profile of air temperature at 0.5m high. Comparing these data with those of a greenhouse with one vent per span (Figs 2 & 3), one can state both a clear diminution of inside air speed (roughly divided by 2) and a straighter air circulation together with an important rise of the inside-outside air temperature difference (roughly multiplied by 2). Thus, decreasing the number of vents strongly affects the inside climate. Vent efficiency optimisation must therefore being searched in a wiser dimensioning of the most "efficient" vents i.e. the first located windward and the last located leeward. A better orientation with respect to the dominant wind is also crucial and this question will be addressed in the next section.

3.4. Effect of the vents orientation and wind direction

Vents orientation with respect to wind direction can strongly affects the ventilation efficiency has shown by the recent studies of Boulard et *al.* (2005) for a plastichouse and Bournet et *al.* (2005) and Ould Kahoua *et al.*, (2006) for a glasshouse. For the three cases, windward vent efficiency was compared to leeward vents efficiency and it was conclude that the windward one was the most efficient. In addition to this comparison, we have also examined the case of a wind parallel to vents opening (Fig. 14). The obtained dynamic and thermal vertical profiles in the direction of the gutters are quite different of those which are observed for a wind perpendicular to the vent openings (Fig. 2). For a wind direction parallel to the vents, air enters in the greenhouse through the whole leeward part of the continuous opening and exits through only a limited area situated at the windward end of the vent opening. Thus, the leeward part of the greenhouse remains cooler than the windward one, and one can notice the expansion of a "bubble" of warm and humid air at the windward end of the greenhouse. Such thermal and dynamic patterns were experimentally observed in a similarly oriented greenhouse by Haxaire (1999), who has also validated the results of the CFD simulations for such an orientation.

Comparing now for the three cases (wind parallel to the vents, leeward and windward orientations) the transverse temperature profiles at 0.5 m high in the middle of the greenhouse (Fig. 15), clearly indicates that the lowest air temperatures were obtained for the wind parallel to the gutters. If the wind is perpendicular to the vents, the windward orientation generates also a moderate inside air temperature elevation and the leeward orientation the highest rise.
One must notices that, paradoxically, the leeward orientation, is also in practice the most frequently observed configuration. As it generates also the highest inside temperature elevation, other questions such as the mechanical strains exerted onto the flaps and the homogeneity of inside climate must also be considered by the greenhouse manufacturers and growers to justify this choice.

4 Conclusions

Combining crop and air interactions by means of customized CFD software's gives a great realism to the greenhouse ventilation and climate numerical simulations. During the last years, emphasis was put on there validation by comparing computed and measured greenhouse climate fields (air speed, temperature and humidity) as well as simulated and measured global air exchange rates. Some discrepancies have been noted through measured and simulated values, but globally, the main phenomena experimentally observed are also confirmed by simulations.

There are now opportunities to use these new tools for improving the greenhouse design and the equipments quicker than with the traditional methods implying real scale prototypes. Three main domains have mainly been explored, i) how deploying greenhouse insect screens while maintaining a fair inside climate and ii) how to optimise ventilation with the existing ventilation facilities and iii) how to improve greenhouse ventilation and climate by means of simple design modifications such as the increase of the greenhouse height or a modification of the shape of the arch.

From this study it can be concluded that screening vent openings with anti Bemisia nets divides by a factor between 2 and 4 air exchange rate and air speed inside the greenhouse and induces a doubling of both the air humidity and temperature rises with respect to outside. For the case of an anti Thrips net, other studies (Boulard *et al.,* 2004) even show that this factor can reach a value of 3.

Structural design elements such as the height of the greenhouse and the shape of the arch influence also strongly the ventilation and climate performances. Especially it was shown that the consequences of an increase of the greenhouse height on the inside climate are asymptotic and that the arch' shape have a strong effect on the inside air circuit and on the ventilation and climate performances.

Optimising the existing vent equipments is also important and it was suggested that orientating the vents parallel to the wind direction was the most efficient but which also generates a strong climate heterogeneity marked by the development of a bubble of warm and humid air at the windward end of the greenhouse. In case of a wind direction perpendicular to the gutters line, the windward orientation is the most efficient but other considerations such as the mechanical strains exerted onto the flaps and inside climate heterogeneity (Bournet *et al.,* 2006) must also be considered.

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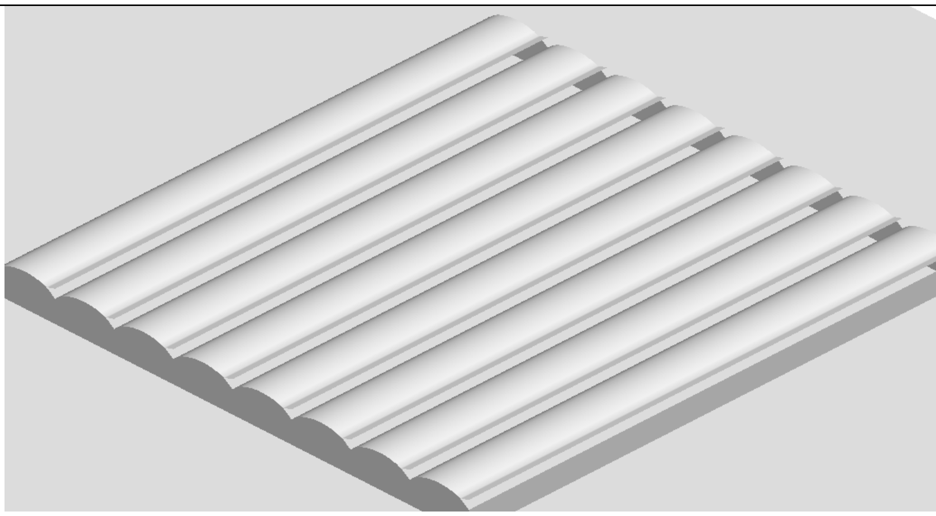


Fig. 1: Scheme of the base type arch type plastic house used for the study: eight spans (8x9.6 m width, 80m length & 5.93 m high) equipped with 1.5 m high continuous vent openings located at gutters height (Multiclair type of FILCLAIR SA).

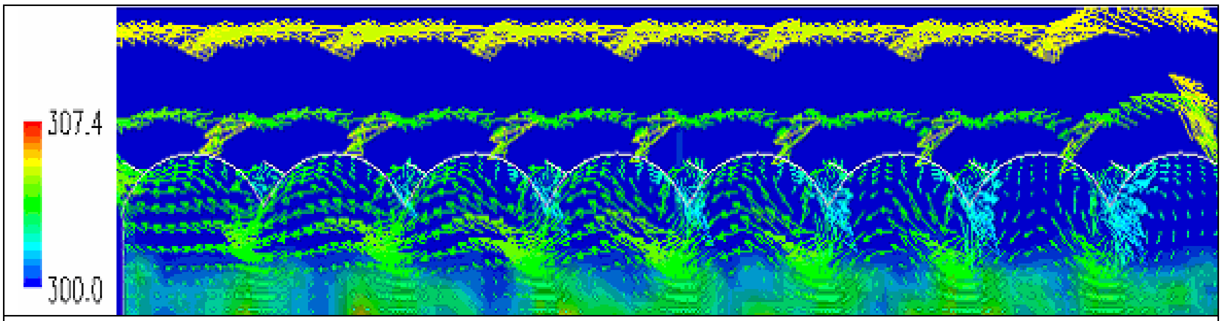


Fig. 2: Vertical cross section of the dynamic (⟶= 2.5 m/s) and thermal (K) fields inside the 8 spans greenhouse for a leeward vent opening orientation..

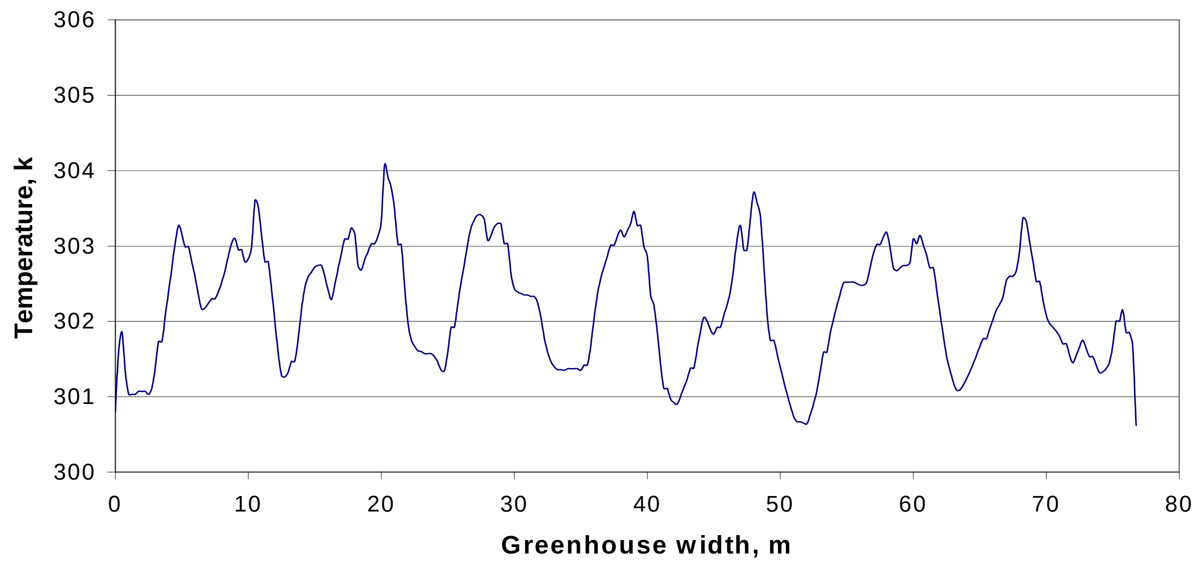


Fig.3 : Vertical cross section of temperature (K) field at 0.5 m high in the centre of the greenhouse deduced from the previous scheme.

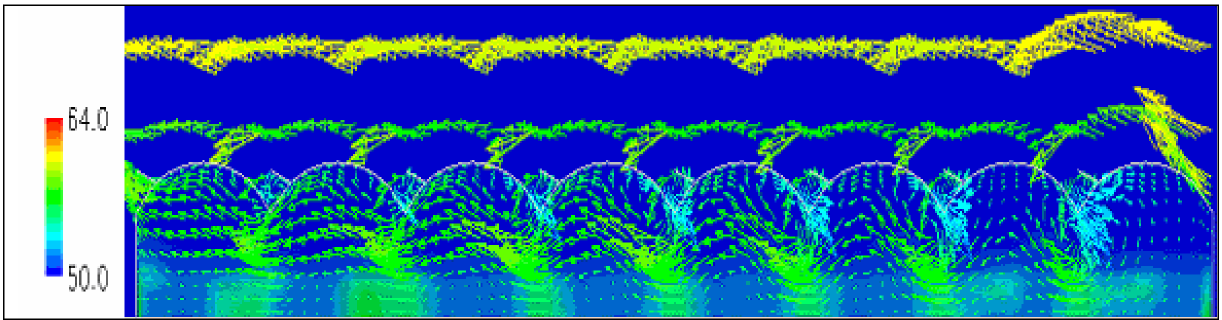


Fig.4: Vertical cross section of the dynamic (⟶ = 2.5 m/s) and humidity (% RH) fields inside the 8 spans greenhouse for a leeward vent opening orientation.

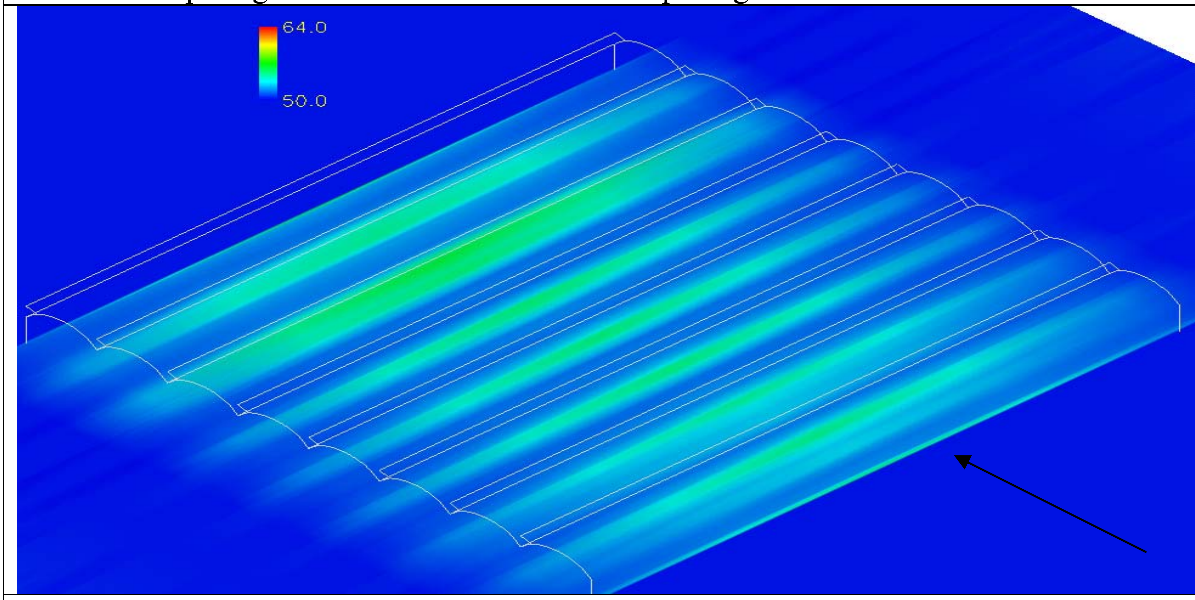
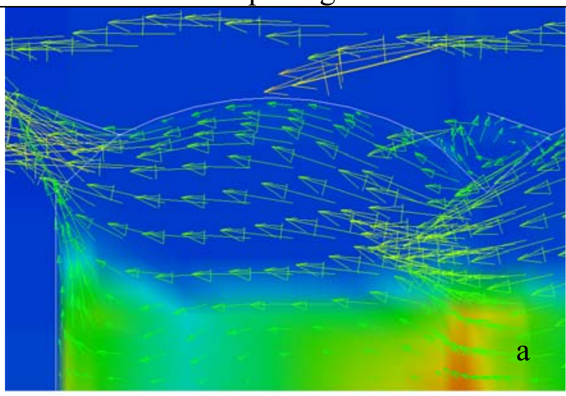
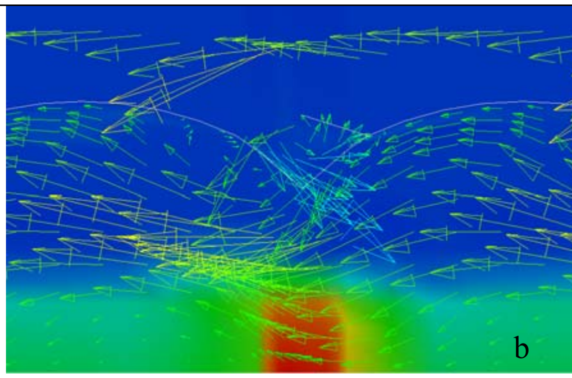


Fig. 5 : Horizontal cross section of the relative air humidity field (%RH) at 0.5 m de high for a leeward vent opening orientation. The arrow indicates the wind direction.





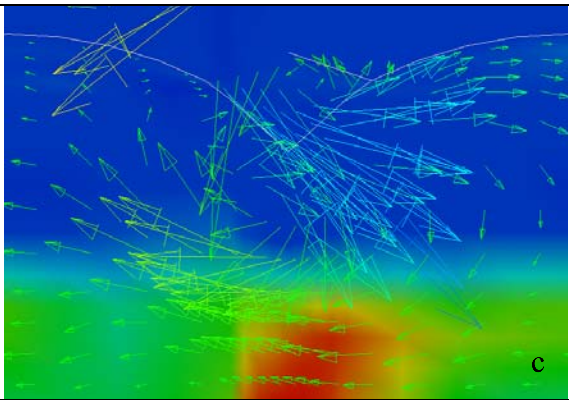


Fig 6 a, b, c : Details of the vertical cross section of the dynamic and temperature (K) fields in the first, fourth and last spans respectively, case of a leeward vents opening.

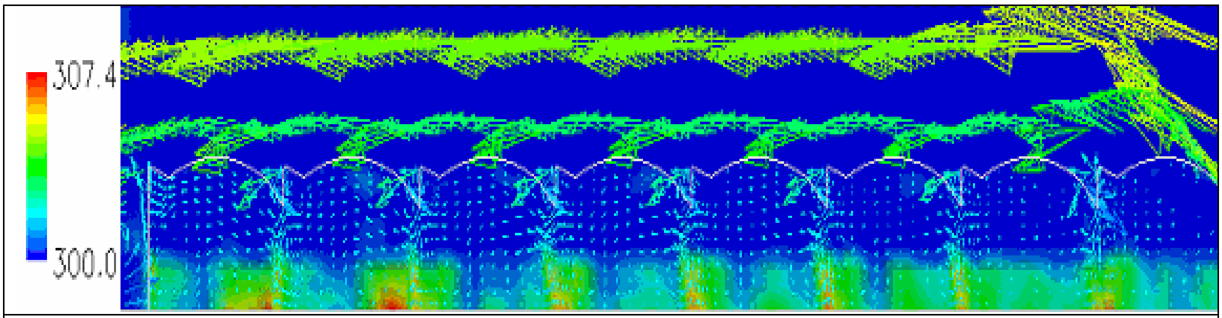
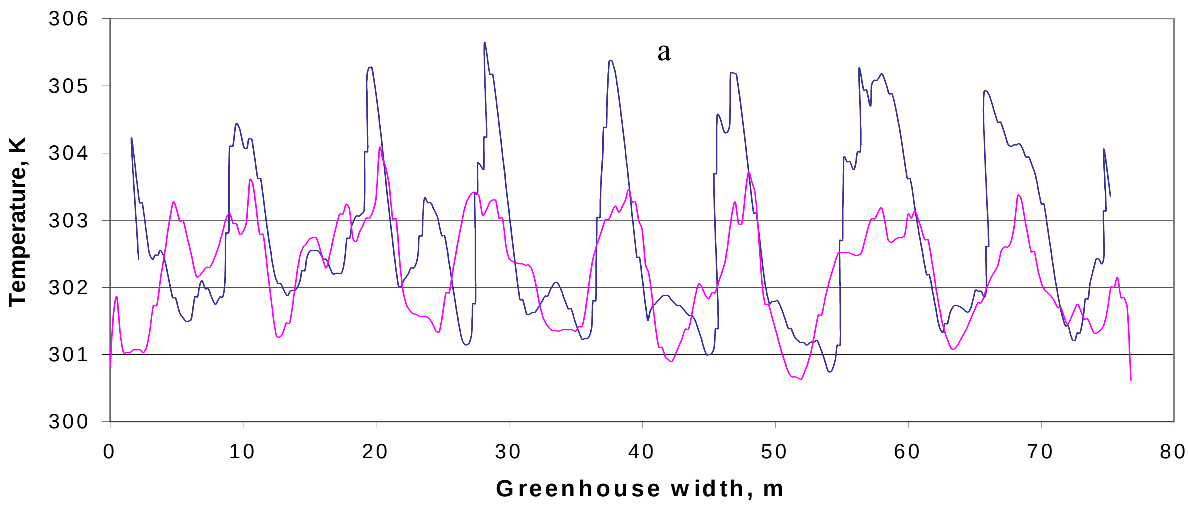


Fig. 7 : Vertical cross section of the dynamic (⟶ = 2.5 m/s) and thermal (K) fields inside the 8 spans greenhouse equipped with anti Bemisia insect proof nets (leeward vents opening)



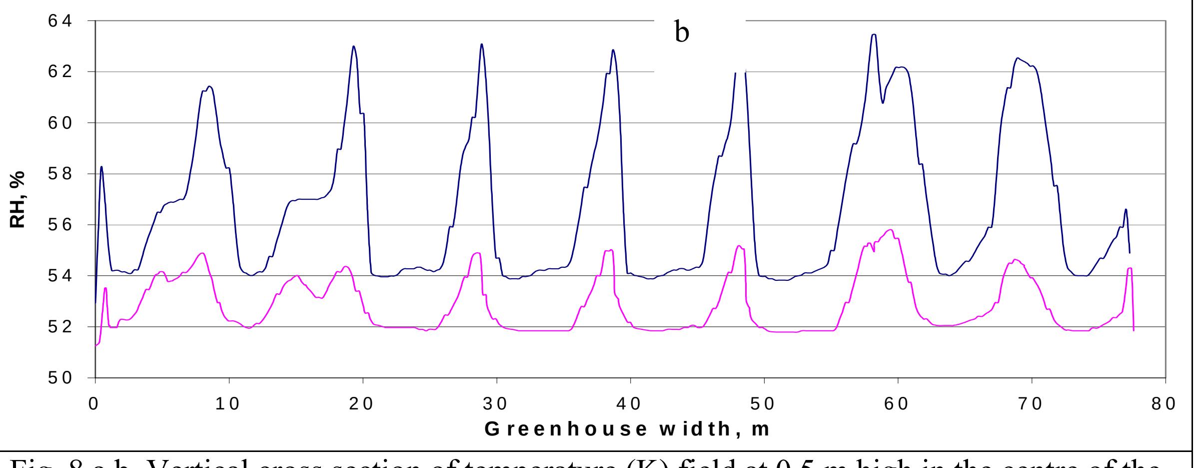
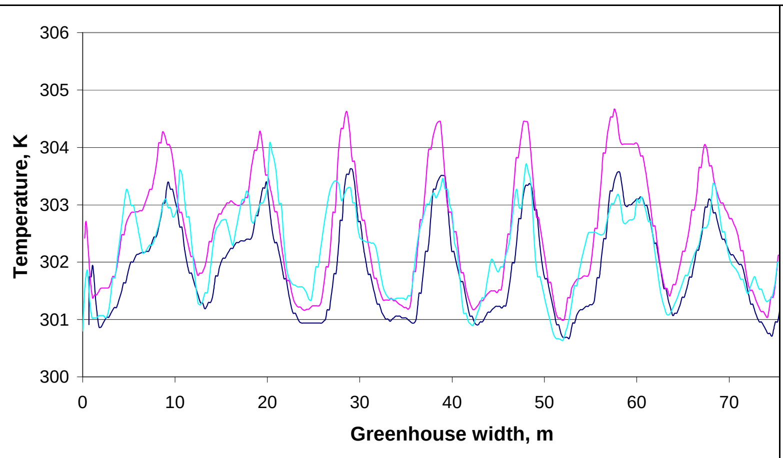
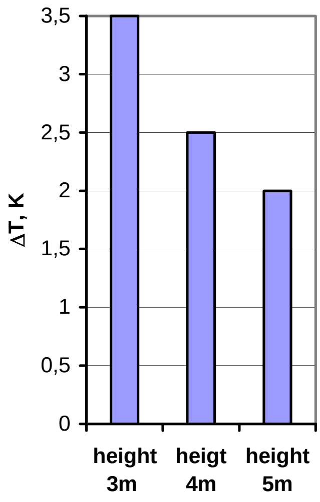


Fig. 8 a,b. Vertical cross section of temperature (K) field at 0.5 m high in the centre of the greenhouse equipped (———) or without (———) anti Bemisia nets : a) Thermal (K) and b) air humidity (%RH) profiles



a



b

Fig 9. Influence of greenhouse height :
a) Vertical cross section of temperature (K) field at 0.5 m high in the centre of 3, 4, 5 m high greenhouse,
b) Asymptotic evolution of the diminution of the average inside outside air temperature difference with the increase of the greenhouse height (at gutters level).

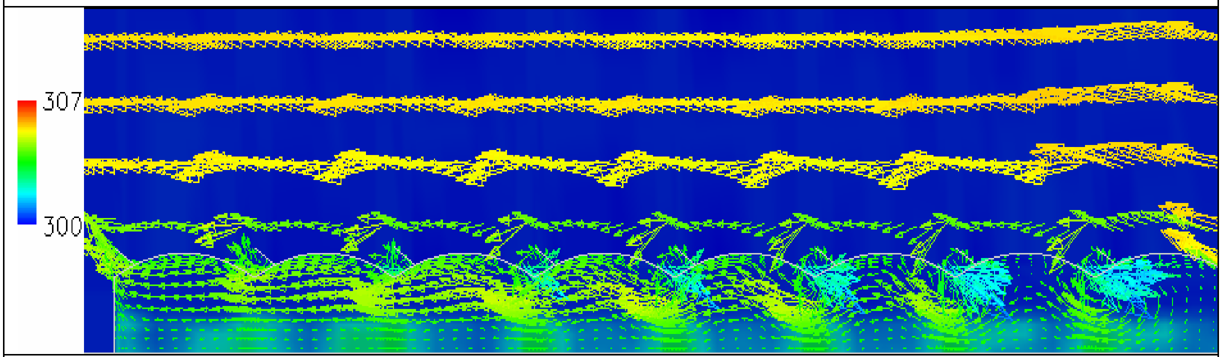


Fig. 10: Vertical cross section of the dynamic (⟶ = 2.5 m/s) and thermal (K) fields inside the 8 spans greenhouse with a flatter arch shape (1.3 m high against 1.93 m normally) (leeward vents opening).

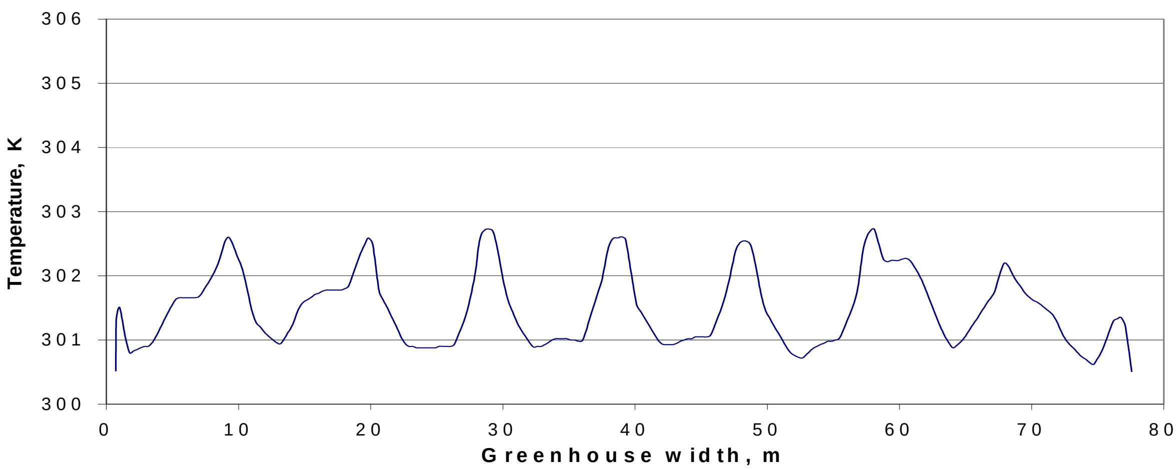


Fig 11: Vertical cross section of temperature (K) field at 0.5 m high in the centre of the greenhouse with a flatter arch shape (deduced from the previous scheme).

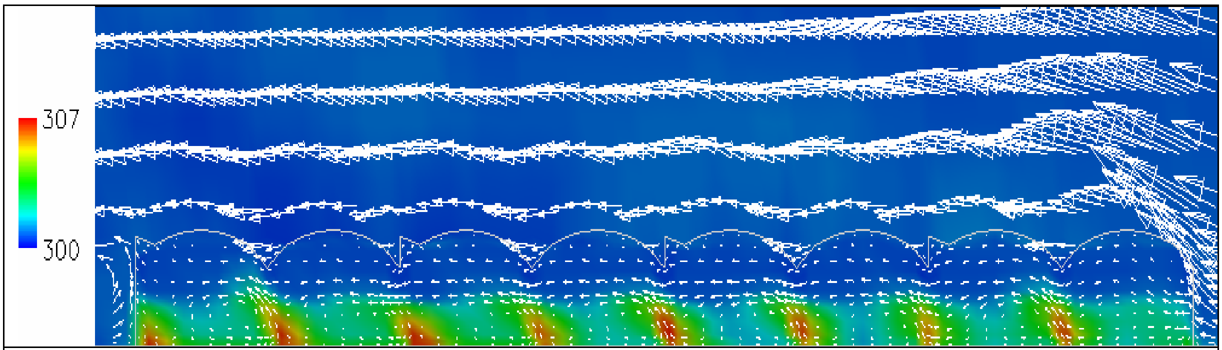


Fig12 : Vertical cross section of the dynamic (⟶ = 2.5 m/s) and thermal (K) fields inside the 8 spans greenhouse equipped with only one line of vent opening per 2 spans (leeward vents opening)..

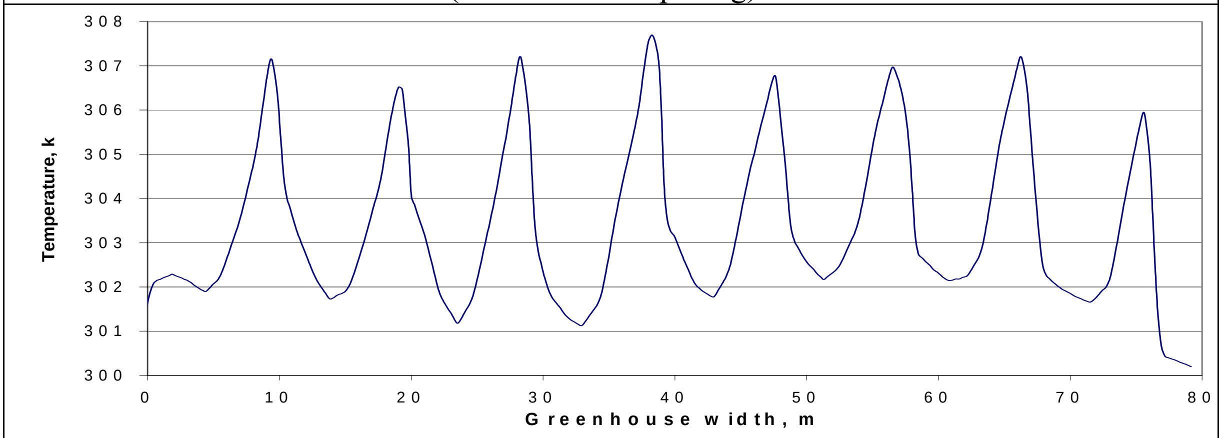


Fig. 13 : Vertical cross section of temperature (K) field at 0.5 m high in the centre of the greenhouse deduced from the previous scheme (with one line of vents opening per 2 spans).

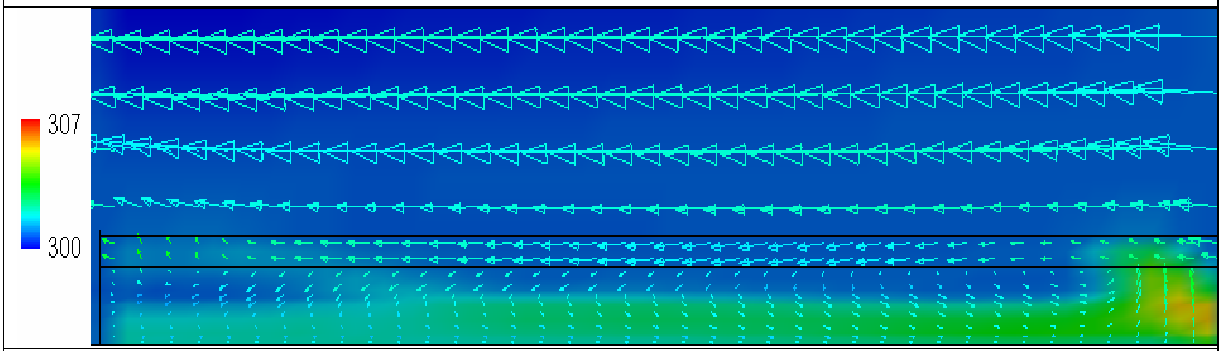


Fig. 14: Vertical cross section of the dynamic (⟶ = 2.5 m/s) and thermal (K) fields inside the 8 spans greenhouse for a wind direction parallel to the vent openings (NB: cross section along the gutters line).

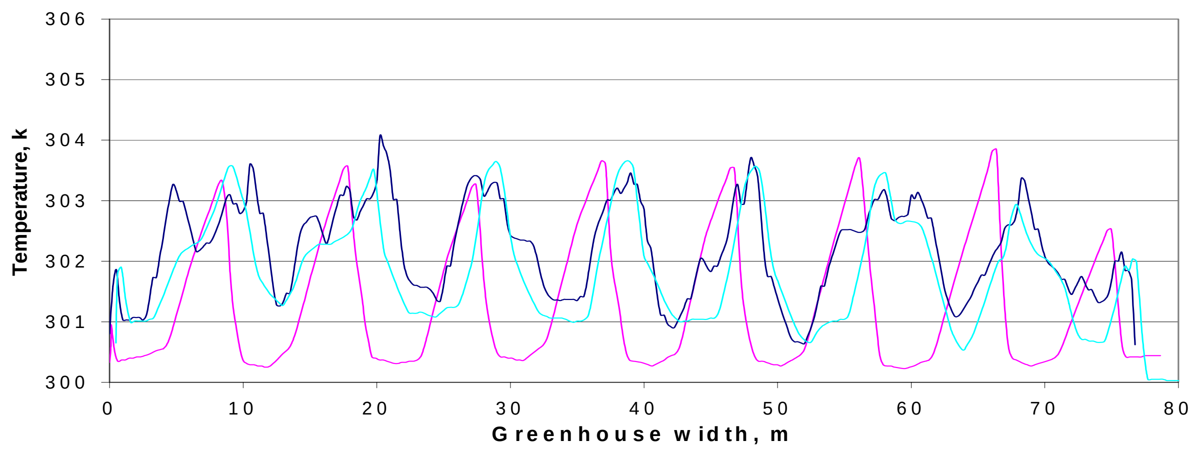


Fig. 15 : Vertical cross section of the temperature (K) field at 0.5 m high in the centre of the greenhouse : Wind parallel to the vents openings; Windward orientation of the vents; Leeward orientation of the vents. NB : Cross section perpendicular to the gutter line.