Field Surveys Combined with CFD Modeling Approach to Investigate the Air flow and Temperature Distribution in a Closed Venlo Greenhouse under Hot and Arid Climate

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Abstract: Greenhouses play an important role in the field of agriculture, allowing the grower to have more control on the environmental factors that govern the behaviour of crops. The interactions of the environmental factors on the inside climate of a greenhouse are complex and involve a set of physical mechanisms that constitute challenges to modellers. To better assess the greenhouse climatic behaviour, a CFD modelling approach was developed and combined with field surveys considering a Venlo, closed greenhouse, under semi arid conditions. Measurements were undertaken at different heights along a vertical cross-section at the centre of the greenhouse. The components of the greenhouse were then integrated inside a CFD distributed climate model. The boundary conditions were inferred from the outside climatic conditions, taking account both of radiative and convective transfers through the walls. Simulations were conducted under pseudo-steady state conditions (i.e. updating the boundary conditions at each time step) all day long, and several scenarios (clear or cloudy day) were simulated to analyse to what extent the inside climate of the greenhouse responds to the outside climate conditions.

Keywords: Airflow and temperature patterns, transient simulations, semi arid climate

1. Introduction

A large variety of protected cultivation systems can be found throughout the world. They range from fully passive greenhouses as in China, to high-tech closed greenhouses in Western Europe [1]. This variety is due to prevailing local conditions and availability of resources. The characterization of the energy balance of the greenhouses for each bioclimatic zone becomes fundamental in order to evaluate the greenhouse feasibility, and to improve its microclimate control [2]. In the next years, agriculture is expected not only to produce food and raw material but also to maintain the landscape and contribute to the reduction of greenhouse gases in the atmosphere. It is anticipated that the new increase in productivity in the next 50 years can also be the result of information and communication technology use in agriculture [3]. Numerical modelling techniques can offer an effective way of accurately quantifying the influence of environment parameters and weather conditions within a virtual environment. Thus, the amount of in situ or laboratory experiments can be reduced considerably. The application of the advanced technology such as CFD in crop production has been concentrated mainly on greenhouses installed in the northern area (Western Europe). Consequently, most publications of CFD greenhouse studies available today deal with northern Europe greenhouse cropping conditions where the crop grows throughout the year in the greenhouse. But few works have been undertaken to optimize the design of greenhouses set up in the arid and semi-arid area of the Southern Mediterranean basin, and little attention was paid to the analysis of the heating efficiency of these greenhouses. Moreover, in most studies involving CFD, no simultaneous solving of the coupled radiative and convective transfers was implemented, but authors imposed measured temperatures or heat fluxes at walls to simulate solar radiation [4], [5]. Suitable models were customized by [6], who considered shortwave and long wave radiation separately and specified the optical properties of the cover. In the southern Mediterranean areas, greenhouses are generally simple shelters with few facilities to control the climate. They are therefore usually too hot in summer to allow crop growth under acceptable conditions. This has driven growers to adopt short cultivation periods which only last 4 to 5 months. The introduction of advanced technology (numerical modelling techniques) in greenhouse agriculture in these regions could enable farmers to improve their decision-making process. The aim of the present work is to provide a thermal analysis of a Venlo glasshouse performance by means of a CFD tool, in order to collect information on the variation of the micro climate parameters, and to develop a better understanding of the greenhouse behaviour. The study gives an insight on the airflow and temperature distributions which establish inside the greenhouse all day long, with boundary conditions inferred from real climatic conditions. The challenge is also to identify its ability to contribute to more efficient decision support systems for protected agriculture applications through the elaboration of a model with could help greenhouse designers to find the best greenhouse shape for each location.

2. Materials and Methods

2.1 Greenhouse experiment description

The experimental work took place in a closed glasshouse of 32 m^2 surface area, without canopy and deprived of any artificial heating system, located at the agricultural research farm of the department of agronomy of the University of Batna (6.110 East, 35.330 North). The greenhouse was a standard 4 m width Venlo type glasshouse (3.60 m high under ridge and 3.27 m high under gutter). It was orientated East–West. The greenhouse was covered with a horticultural glass of 4 mm thickness. The measurements points were located in the middle of the greenhouse and distributed along a cross-section at the centre of the greenhouse in the same vertical plane. Fig. 1 provides a schematic view of the facility and shows the different probes used to measure the temperature and the relative humidity. The temperature and relative humidity of the interior air were recorded by means of a data logger (OAKTON Logger Plus) which is a remote sensing system. The temperatures of the solid surfaces (ground, underground and wall surfaces of the cover) were measured every 2 s with thermocouples, and then averaged over 30 min periods. All the above-mentioned measurements were collected on a data logger system (Campbell Scientific Micro logger, CR3000). The outside climatic conditions were measured by a weather station installed on the roof at one meter height above the greenhouse.

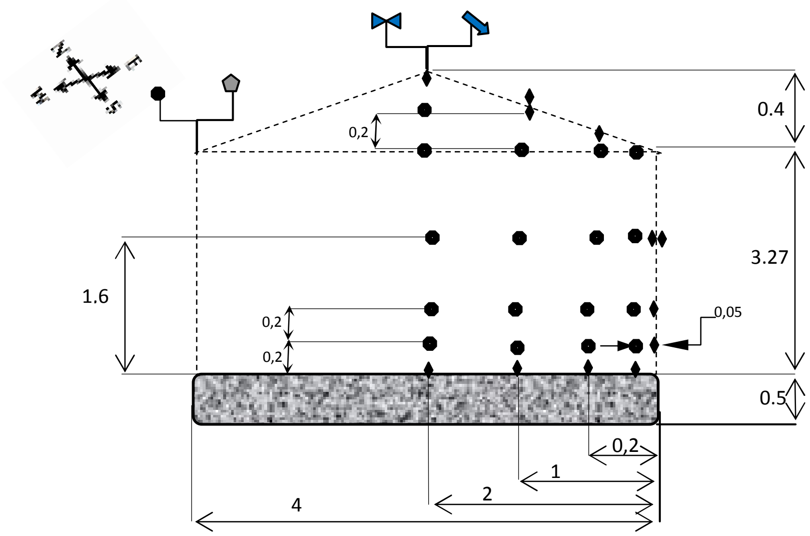

Figure 1: Experimental setup view (lengths are in meter).
Humidity and temperature sensors: (●) ; Thermocouples:( ) ; Wind vane: ( );
Cup anemometer ( ) ; Pyranometer: ( ).

2.2 Greenhouse modelling and CFD model details

In this work, two-dimensional unsteady simulations were performed using a commercial CFD software package (Fluent 6.1). The flow fields were analysed using a model based on Reynolds averaged Navier–Stokes equations with the Renormalize Group (k–ε) model. The k–ε model is widely used in the modelling of indoor airflows and proved to be efficient in greenhouse studies [7]. The second-order upwind scheme was adopted for the convection term, and a semi-implicit method for pressure-linked equations (SIMPLE algorithm) was used for steady-state analyses. Convective, conductive and radiative heat transfers were considered. The Boussinesq approximation was adopted to take account of the buoyancy effects, assuming a linear relationship between temperature and density. A large calculation domain (30 m long, 30 m wide and 20 m high) including the greenhouse was considered. The computational grid used Cartesian coordinates and a finer resolution was imposed in critical portions of the flow subject to strong gradients. The mesh was coarser in the centre of the greenhouse while it was denser near the cover and ground surface close to solid surfaces. The final grid contained 12 000 cells. The boundary conditions prescribed a null pressure gradient at the limits of the computational domain, and wall-type boundary conditions along the floor and roof, whereas the side walls were treated as isotherm conditions (by setting the measured temperatures which were updated at each time step). A logarithmic wind profile was imposed at the entrance of the calculation domain 15 m from the greenhouse as a dynamic boundary condition for the external air together with a uniform temperature profile. Fixed air temperatures were imposed along the ground. As no radiation was simulated directly, the solar radiation was taken into account in an indirect way in the model by setting the measured temperatures (which result from the solar radiation and absorption coefficients) at the glass cover. All these boundary conditions were updated at each time step. The initial conditions were chosen as follows: the pressure p was equal to the atmospheric pressure p_0; the horizontal velocity u and the vertical velocity v were taken equal to 0 and the temperature of the inside air of the greenhouse was taken as $T=T_0=300$ K. The convergence criterion for all variables was 10^{-6}.

3 Results and Discussion

3.1 Noctural period

Experiments and simulations were conducted for two contrasted days: a cloudy day on May 2nd 2011 and a clear day on May 13th 2011. Calculations were carried out with a 30 min time step and the climatic parameter distributions were analysed. During the nocturnal periods, the conduction heat flux through the ground surface was ascending; due to the fact the sand layer was transferring heat upwards. The average values of the conduction flux during the night correspond to an energy release from the ground of 38.82 and 45.03 Wm^{-2} respectively for the cloudy and clear night. During the first night for instance, the ground supplied enough energy to compensate the radiative losses, which represented the main loss component (28.04 Wm^{-2}). Concerning the interior air, the temperature and the horizontal velocity patterns (Fig. 2, I, c) and (Fig. 2, II, c) show a movement of the air directed upwards which is due to the natural convection induced by the air density gradient. The air located near the ground surface moves up, and reaches its maximum velocity near this surface for both nights. This was due to the heating of the air by the thermal energy released from the soil during the night. The average values of the convective heat flux coefficient between the ground surface and the interior air are plotted against the temperature gradient (surface ground - interior air) in Fig. 3a. It can be seen that the convective coefficient varied according to a power law function of the temperature gradient ($h=7.49\Delta T^{0,33}$) and a good correlation was found (R^2 = 0.90). Fig. 3b shows the variation of the convective coefficient between the interior air and the interior wall of the cover versus the temperature gradient (interior air - interior wall). Here again, the convective coefficient varied according to a power law function of the temperature gradient ($h=3.59\Delta T^{0,33}$) with a correlation coefficient close to unity (R^2 = 0.97). Results confirm that the convective heat transfer inside the greenhouse was induced by free turbulent convection mechanisms and depended on the temperature difference between the inside surface (soil or wall) and the interior air temperature [8]. The net heat flux radiation on the interior wall represented the main part of the heat supply to the wall. The reverse was also true for the outside wall, where the radiation losses prevailed. The net radiation on the outside wall reached a high value (56.04 Wm^{-2}) for the second day (13rd May). Simulated temperature distributions show that only the ground surface temperatures (Fig.2, I, c) were higher than the interior air temperatures during the night, meaning that this surface was the only one to bring heat to the interior air during the night. Conversely, the walls and roof all contributed to heat losses from the interior air, since the interior air was only heated by the thermal energy released from the soil. Fig4, a and b show that the interior air temperature was higher than the temperature of the walls during the night for both days. Results also clearly show that the experimental values were in agreement with the simulated ones.

3.2 Diurnal period

Predicted air temperatures profiles (Fig 4a and b) also suggest that greenhouse walls and soil surface absorbed more heat (solar radiation) than expected during the diurnal period. During daytime, the heating of the air was mainly due to this phenomenon i.e. absorption of the solar radiation by the walls and the ground. On contrary, the cooling of the air was due to the convective losses (sensible and latent) along the roof, and to the heat losses by infiltrations through the structure of the greenhouse (the wind effect). During the clear day, predicted air temperature profiles (fig. 2, I, a) show that the surface temperatures of the soil and walls were higher than the interior air temperatures (Fig. 4,a) meaning that these surfaces brought heat to the interior air. However, on the cloudy day, the walls and roof all contributed to heat losses from the interior air (Fig. 4, b), while the soil surface was the only one to warm the interior air, not enough however to compensate the substantially reduced solar insulation on the cloudy day. Simulations also show that the temperatures in the centre of the greenhouse were relatively homogeneous between 0.2 and 3 m height, while they strongly vary in the vicinity of the wall surfaces. The temperature decreased near the roof surface and increased near the soil surface (Fig. 2, I). The velocity patterns (Fig. 2, II) show the movement of the air during the cloudy day, the air velocity reaching its maximum values near the roof at midday and near the soil at 6pm, (Fig. 2,II. a, b). The reverse was also true for the clear day, the air velocity reaching its maximum values near the roof for all day long. This phenomenon was due to the heating of the air during the first hours of the day, its quick intensification, and its localisation in the upper zone of the greenhouse near the roof.

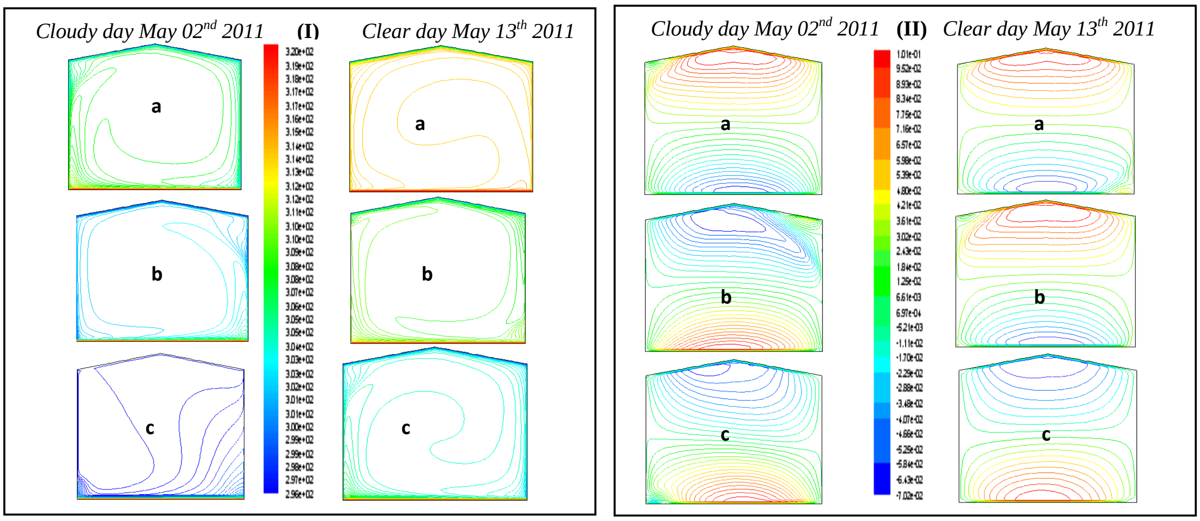

Figure 2: Temperature distribution (**I**) and horizontal component of the air velocity (**II**) in a vertical plane in the middle of the greenhouse at different instants
(a): t = midday, (b): t =6 pm, (c): t = midnight

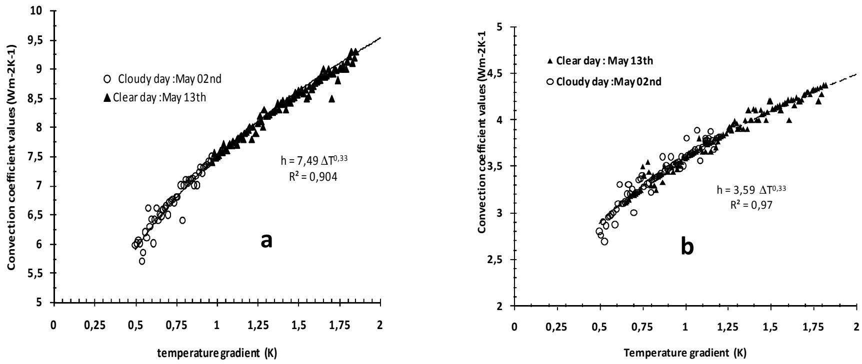

Figure 3: Convection coefficient values according to the temperature gradient during both measurement periods; (a): Convection coefficient values at the ground surface; (b): Convection coefficient values at the interior wall of the cover.

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b

a

Figure 4: Horizontal profiles of the temperature of the interior air of the greenhouse 1.5m high above the ground surface: a) Cloudy day, b) Clear day.

4. Conclusions

The interactions of the environmental factors with the thermal behaviour of the inside air of a closed glasshouse during two contrasted days (cloudy and clear) were simulated. The simulation took account of the real outside climatic conditions with boundary conditions inferred to the outside environmental factors. The first day represented a cloudy day and the second day represented a clear day of the spring season for a greenhouse located under semi arid climate in the southern Mediterranean areas (Batna, Algeria). Two cases are investigated (nocturnal and diurnal) periods. From the results it comes out:

- During the nocturnal period, only the soil surface temperature was higher than the interior air temperature, so this surface was the only on to contribute heat to the interior air by the thermal energy released from the soil. The basic mechanism of heat transfer inside the greenhouse is the convection due to the heating of the air by the thermal energy released from the soil, but close to the walls and the roof the thermal radiation exchange allowed influencing the temperature distribution.
- During the diurnal period, the walls and ground surface absorbed more heat than expected. Where incident solar radiation and heat storage are allowed to influence the temperature.; The distribution of the temperature and air speed was studied and there temporal variation show that the temperatures in the centre of the greenhouse remained relatively homogeneous, while they substantially vary in the vicinity of the wall surfaces; the air velocity reached its maximum values near the roof at midday and near the soil at 6pm for the cloudy day. For the clear day, the air velocity reached its maximum values near the roof for all the diurnal period.

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