Web-based estimation model of natural ventilation efficiency in greenhouses using 3D computational fluid dynamics

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Abstract: In this work a model to estimate the efficiency of natural ventilation in a commercial twin-span greenhouse is presented. A numerical simulation approach was adopted using the theory of three-dimensional computational fluid dynamics (CFD). With this approach, it was able to generate three-dimensional patterns for temperature and airspeed inside the greenhouse, using specific boundary conditions. The CFD simulation was applied to an empty twin-span greenhouse with a floor area of 980 m^2 with low density polyethylene cover and two side continuous opening and one roof opening. The simulation assumed a sunny summer day with four different airspeeds vertical to the long side of the greenhouse and three different temperature values. Temperature and airspeed data of the entire greenhouse environment were generated by means of CFD simulation and the obtained results were of high accuracy. Each span of the greenhouse was then notionally divided into ten blocks. Average values of the CFD-generated data were used for the parameters estimation of each block. Interpolation was used on the average values of temperature and airspeed of each block to estimate values at different boundary conditions than those that were used during the CFD simulation. This model, which has very low computational demands in comparison with the original CFD simulation model, is incorporated into a web-based application for real-time predictive modeling of temperature and air speed patterns of the greenhouse environment. The web system consists of three main components: the user interface the interpolation process and the output interface.

Keywords: CFD, greenhouse natural ventilation, greenhouse climate, web-based model.

1. Introduction

The main factors which characterize and influence the greenhouse environment are light, humidity, temperature, carbon dioxide concentration and ventilation rate. Ventilation is the main control method of the greenhouse's high temperatures. Natural ventilation is mostly used nowadays since it requires less energy, equipment and power than other forms of ventilation. The performance of ventilation plays an important role to the production, affecting not only the climate of the greenhouse, but the qualitative and quantitative properties of the crop product as well.
With the aid of computational flow dynamics, a simulation of real climate conditions and greenhouse structure details can be implemented, based on given conditions. Computational fluid dynamics (CFD) is a simulation approach that is used to study the behavior of all kinds of transport processes which involve fluid flow, heat and mass transfer. Reichrath and Davies (2002) have recently published a review paper that presents the state-of-the-art of the application of CFD for the modeling of the greenhouses.

In this work a model to estimate the efficiency of natural ventilation in a commercial twin-span greenhouse is presented. A numerical simulation approach was adopted using the theory of three-dimensional computational fluid dynamics (CFD). With this approach, it was able to generate three-dimensional patterns for temperature and air speed inside the greenhouse, using specific boundary conditions for outside temperature, air speed and direction, relative humidity, greenhouse geographical position and orientation, and position of the sun.

The model was applied to an empty twin-span greenhouse with a floor area of 980 m^2 with low density polyethylene cover and two side continuous and one roof openings.

Temperature and air speed data of the entire greenhouse environment were generated by means of CFD simulation and the results obtained were of high accuracy. Each span of the greenhouse was then notionally divided into ten blocks of 3m height, 7m length and 7m width. This height was at the position of the gutter. Average values of the CFD-generated data were used for the parameters estimation of each virtual block. This approach was necessary because of the high computation demands of the program and the vast amount of data produced. The availability of results on a block level could be useful for prediction purposes particularly in the case of the presence of some specific cultivation crop in the greenhouse.

Interpolation was used on the average values of temperature and air speed of each block for the two spans of the greenhouse to estimate values at different boundary conditions than those that were used during the CFD simulation. This model, which has very low computational demands in comparison with the original CFD simulation model, was incorporated into a web-based application for real-time predictive modeling of three-dimensional representation of temperature and air speed patterns of the greenhouse environment. The web system consists of three main components: the user interface, the interpolation process and the output interface.

2. Theory

2.1. Mechanisms Affecting Natural Ventilation Airflow

Ventilation is caused by external wind force (wind effect) and buoyancy force (thermal effect) based on the temperature rise (temperature difference between internal and external air). Natural airflow inside greenhouses is a combination of the effects of both thermal and wind forces.

2.2. CFD

2.2.1 Principles

The computational domain, in which a CFD simulation will take place e.g. the greenhouse plus its environment, must be well defined. This domain is divided into small cells, the control volumes, in each of which a value for the simulated variables is calculated and conservation equations are applied to each of these control volumes. Rate equations define the transfer rate of a transportable property. The computational effort required can be large and is dependent on the number of computational cells in the domain, the number of variables solved in each cell and the kind of simulated transport processes.

2.2.2. Governing Equations

The used CFD code (Airpak, 2002) solves the Navier-Stokes equations for transport of mass, momentum, species, and energy when it calculates laminar flow with heat transfer. RNG k-ε transport equations (Yakhot and Orszag, 1986) are solved when the flow is turbulent and the Discrete Ordinates (DO) Radiation equations (Raithby and Chui, 1990; Chui and Raithby, 1993) for radiative heat transfer.

3. Materials and methods

3.1. Greenhouse characteristics

An empty twin-span greenhouse (Figure 1) with a floor area of 980 m^2 with low density polyethylene cover, two side continuous openings and one roof opening were used. The Greenhouse characteristics are presented in the Table 1.

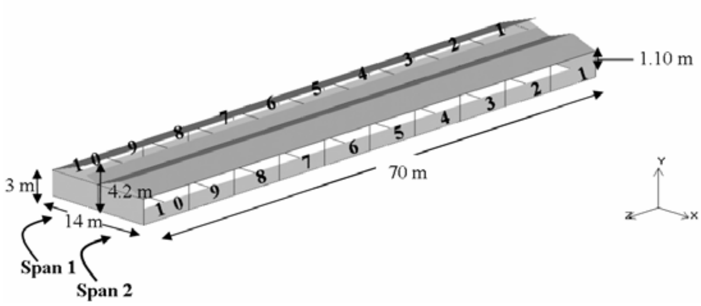


Figure 1. The greenhouse

Greenhouse characteristics	
Scale	No scale Continuous roof vent Continuous side openings
Ridge height	4.2 m
Gutter height	3.0 m
Width	14.0 m
Length	70.0 m
Roof vent width	1.10 m
Roof Vent pivot point	4.2 m
Roof vent opening angle	19^o
Side opening width	1.12 m
Latitude	37.58^o
Longitude	23.32^o
Orientation	East-West (parallel to greenhouse length)
Ground emissivity	0.9
Cladding material	Low density poly-ethylene (LDPE)
Cladding thickness	10^{-4} m
Cladding visible transmittance	0.75

Table 1. Greenhouse characteristics

3.2. CFD simulation

Airpak 2.10 Fluent Inc. software was used for this study. Tree-dimensional simulations were carried out and all were steady-state. Both buoyancy and thermal effects were considered. The ground characteristics were considered to be dynamic and the air was assumed real and not an ideal gas. The simulation assumed a sunny summer day with four different air speeds vertical to the long side of the greenhouse and three different temperature values. Boundary conditions were selected to represent a sunny summer day. In particular, in all simulations the computational domain was large enough to eliminate side effects of the boundaries on the pressure distribution around the greenhouse. The size of the computational domain was much larger than the greenhouse (Figure 2).

At the outlet boundary a fixed static pressure condition was chosen, being with relative to the ambient value. The RNG (ReNormalisation Group) turbulence model was used. The grid was an unstructured hexahedral mesh with higher density in the near wall regions around and inside the greenhouse. The CFD simulation numerical parameters are presented in the Table 2.

Temperature and air speed data of the entire greenhouse environment were generated by means of CFD simulation and the obtained results were of high accuracy. Figure 3 displays plane cuts for the temperature and airspeed velocity.

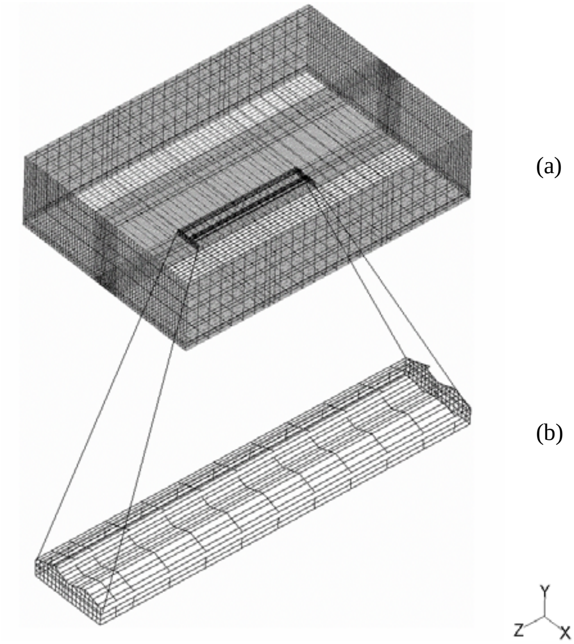


Figure 2. (a) The computational domain, (b) enlarged view of the greenhouse

Numerical parameter	**Description**
Mesh size	Width x Height x Length=114m x 40m x 170m
Turbulence model	RNG model
Outer boundary pressure	Fixed
Outer boundary temperature	Fixed. Cases:20°C, 25°C, 30°C
Outer boundary airspeed	Fixed. Cases: 0m/s, 2m/s, 5m/s, 10m/s Direction: North->South (perpendicular to greenhouse length)

Table 2. CFD simulation numerical parameters

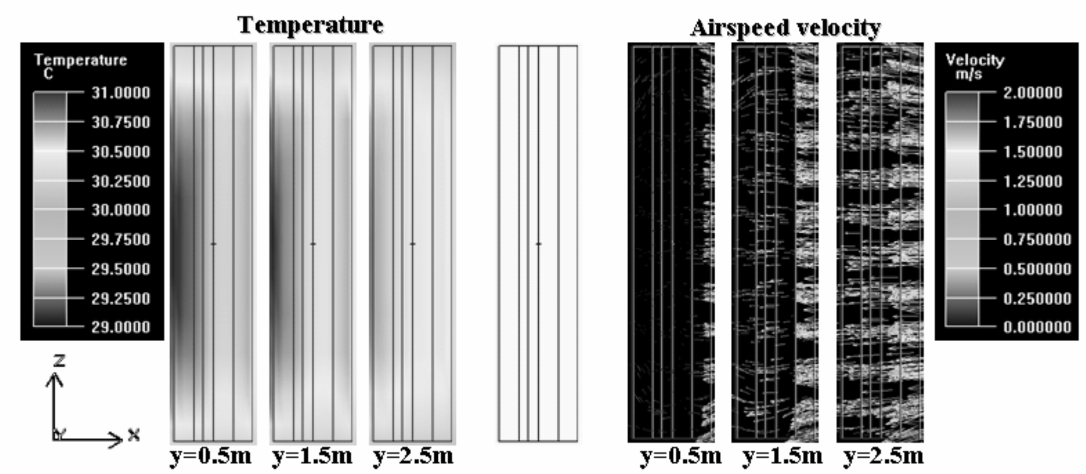


Figure 3. Plane cuts for the temperature and airspeed velocity.

4. System Architecture

The web system (Figure 4) consists of three main components: the user interface which contains the required input variables (external temperature, air speed and desired block(s)), the interpolation process and the output interface actual values, plots and alert messages. This system is a Java applet and therefore is platform independent. It requires Java JDK 1.4 (or later) API and Java 3D SDK API to run.

Temperature and air speed data of the entire greenhouse environment are already calculated by the CFD simulation. CFD-generated data, which are location (x,y,z), temperature (T), airspeed components (Ux, Uy, Uz), are stored in a file. Each span of the greenhouse is then notionally divided into ten blocks of 3m height, 7m length and 7m width (Figure 1). This height was at the position of the gutter. The applet allows the user to establish a connection to the data. After the connection the user enters the desired data (temperature, airspeed and block(s)). Average values of the CFD-generated data are used for the estimation of each virtual block parameters (average temperature, air velocity and airspeed components). This approach was necessary because of the high computation demands of the program and the vast amount of data produced. The interpolation process firstly calculates the interpolated data for the user airspeed and then calculates the interpolated data for the user temperature.

Before the interpolation process the system locates the suitable CFD data from the available generated data. For each boundary temperature and airspeed the system selects the suitable CFD data sets. These data sets are the result of the predefined boundary values which bounds the user values (U_o^{User}, T_o^{User}). Interpolation is used on the average values of temperature and air speed of each block for the two spans of the greenhouse to estimate values at different boundary conditions than those that were used during the CFD simulation. The mechanics of the process are depicted in Figure 5.

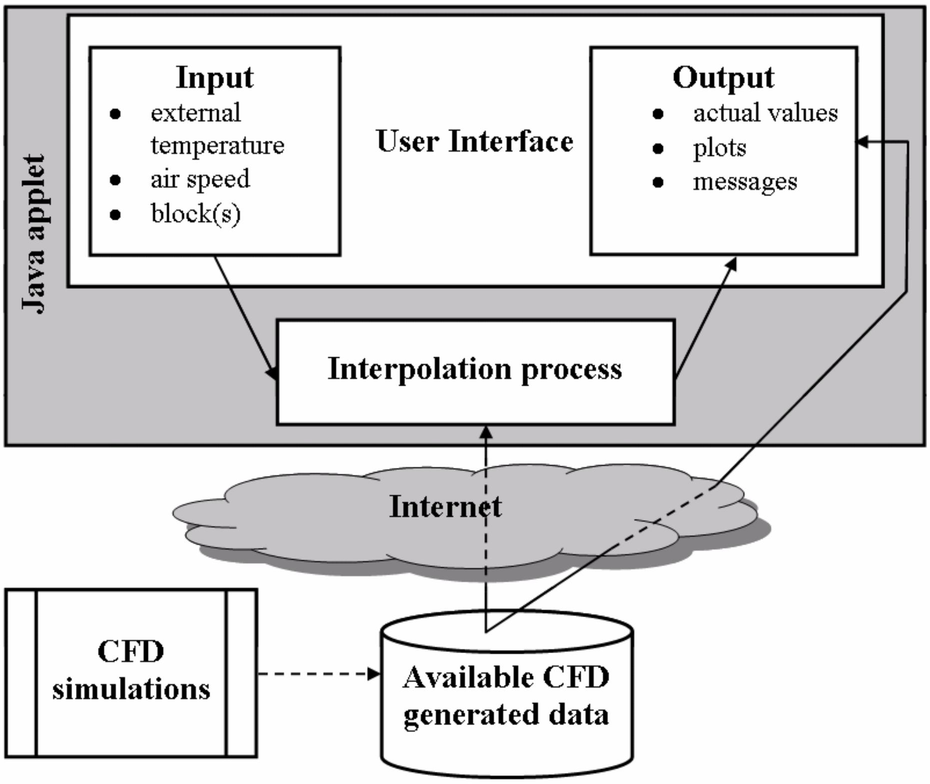


Figure 4. Web system general architecture.

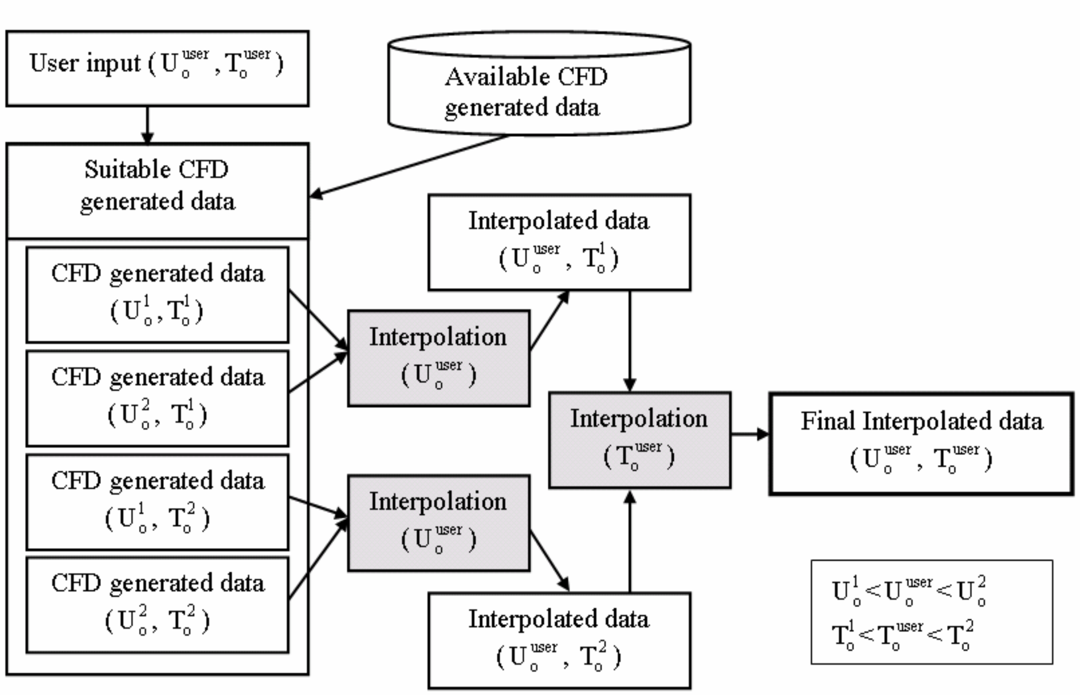


Figure 5. The interpolation process.

5. Results and Discussion

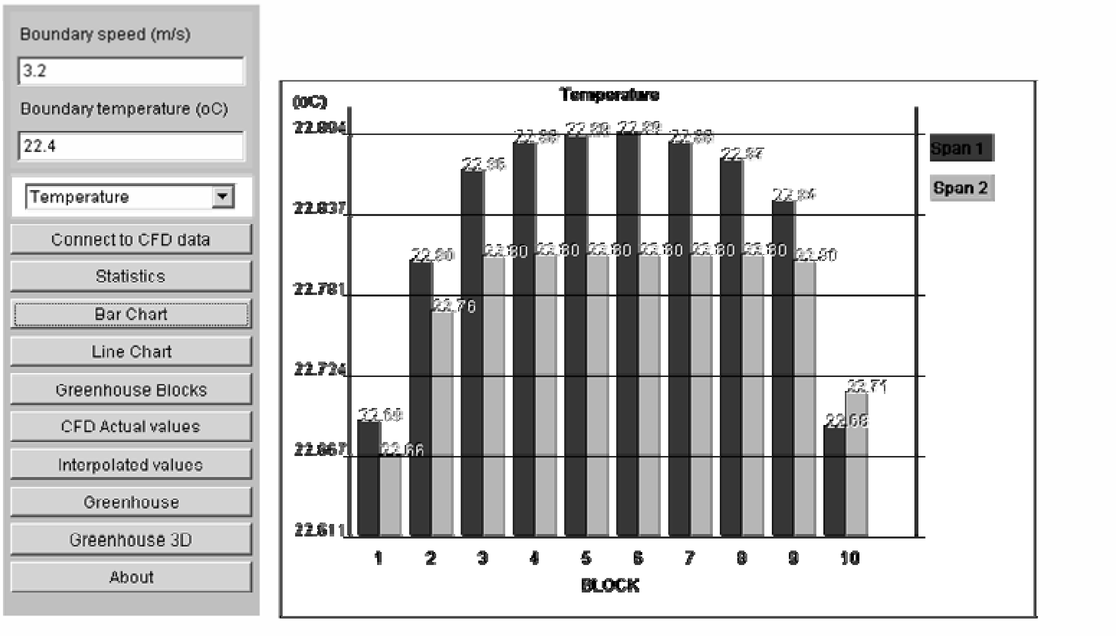
The graphical user interface (GUI) is automatically generated as a Java applet or stand-alone interface. The screen shots (Figure 6) show the GUI and some results of the model. The available menu choices of GUI and their actions' descriptions can be seen in Table 3.

Menu choice	**Action description**
Boundary speed (Input Box)	The user inputs the desired Boundary airspeed in m/s.
Boundary temperature (Input Box)	The user inputs the desired Boundary temperature speed in °C.
Variable choice list (List)	The user choices the desired variable. Available variables: Temperature, Airspeed, Airspeed X component, Airspeed Y component, Airspeed Z component.
Connect to CFD data (Button)	Establish a to the CFD data.
Statistics (Button)	Displays statistics values of the data.
Bar Chart (Button)	Displays a bar chart of the interpolated data.
Line Chart (Button)	Displays a line chart of the interpolated data.
Greenhouse Blocks (Button)	Displays the position of each greenhouse block.
CFD Actual values (Button)	Displays the CFD generated data.
Interpolated values (Button)	Displays the Interpolated data.
Greenhouse (Button)	Displays the greenhouse structure characteristics.
Greenhouse 3D (Button)	Displays an interactive 3D view of the greenhouse.
About (Button)	Displays important characteristics of the applet.

Table 3. Available menu choices and their action description

From the results in Figure 6a, we can conclude that the temperatures of each block of Span 2 are higher than the temperatures of the respective blocks of Span 1. The opposite occurs in the case of airspeed (Figure 6b). The results may differ according to the user's inputs (i.e. lower boundary airspeed or higher boundary temperatures).

The proposed model has extremely low computational and time demands, in comparison to the original CFD simulation model and can be used for real-time estimation of temperature and airspeed patterns of the greenhouse environment. The availability of results on a block level could be useful for prediction purposes particularly in the case of the presence of some specific cultivation crop in the greenhouse. The continuation of this work will focus on three directions: i) additional available boundary conditions at the CFD simulation level, ii) capability of user-defined block sizes at the web-system level and iii) inclusion of specific types of cultivation crop inside the greenhouse.

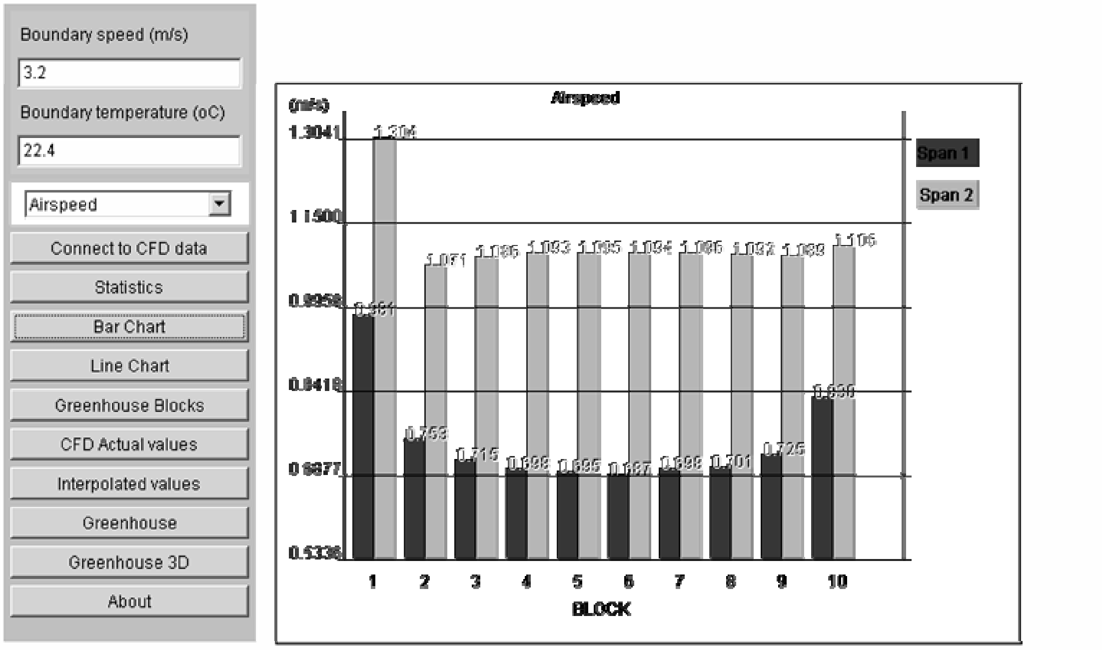


Boundary speed (m/s): 3.2

Boundary temperature (oC): 22.4

Temperature

(a)



Boundary speed (m/s): 3.2

Boundary temperature (oC): 22.4

Airspeed

(b)

Figure 6. Model results. a) Internal temperature and b) Internal airspeed of each block.

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Acknowledgments

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