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Porous Media in the Simulation of Greenhouse Crops Using the Naïves Bayes EM Algorithm

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Abstract

The porous media approach has become more popular thus, it solves the equations of motion and energy numerically and therefore obtains detailed distributions of temperature and airspeed. However, those models are not allowed to forecast the relationships between the porosity of the volume of the crop with respect to the variables that comprise the climate in natural ventilation greenhouses at the same time in terms of probability. A porous media model of the crop and its approximations were developed and analyzed through non-supervised Bayesian Networks clustering, with the aim of determining the influence of porous media in function to the density crop, over the climate conditions in a natural ventilation greenhouse. Also, a naïve Bayes model unsupervised by the EM algorithm, initialized with random parameters was developed. The resulting model maximized the likelihood of the training data set. The relationships between the pressure drops in the flow limits at the crop were established. Porosity is directly influenced by humidity, temperature and slowly to CO2 concentration. Solar radiation, speed air and slowly the height are inversely influenced with the porosity. Naïve Bayes EM application to a CFD model has been providing a greater understanding of the interactions between the variables.

Indexing terms/Keywords: Models of Computation, Bayes Methods, Numerical Analysis, Digital Simulation.

Subject Classification: Numerical models in the greenhouses

Type (Method/Approach): Computational Fluid Dynamic and Bayesian networks in the greenhouses

Introduction

In the last decade, it has extended the use of numerical methods such as Computational Fluid Dynamics(CFD), which, based on the Navier-Stokes, has proven to be an excellent tool to develop models. The porous media approach has been widely used in recent years to simulate the insect screens and analyze the greenhouse microclimate. This analysis has become more popular because it solves the equations of motion and energy numerically and therefore obtains detailed temperature and air distributions profile inside a greenhouse. Typical features of a CFD model, required in ventilation studies, include airflow ability depending on the properties of the model; implement user-defined functions and the flow pattern through porous media. Many authors [1 – 8] that have used CFD approach noted that employing a porous media zone, regardless of the shape and dimensions, the physical objects can be simulated with features similar airflow to avoid any discontinuity in the meshing of the computational domain. Porous media have influence over the climate conditions; Chen [9] determined with a CFD model, that the windbreak used in agriculture to prevent wind damage to the crop modifies microclimate by the momentum distribution of wind and turbulence. Figure 1 shows the effect of wind protection in the natural ventilation of greenhouses.

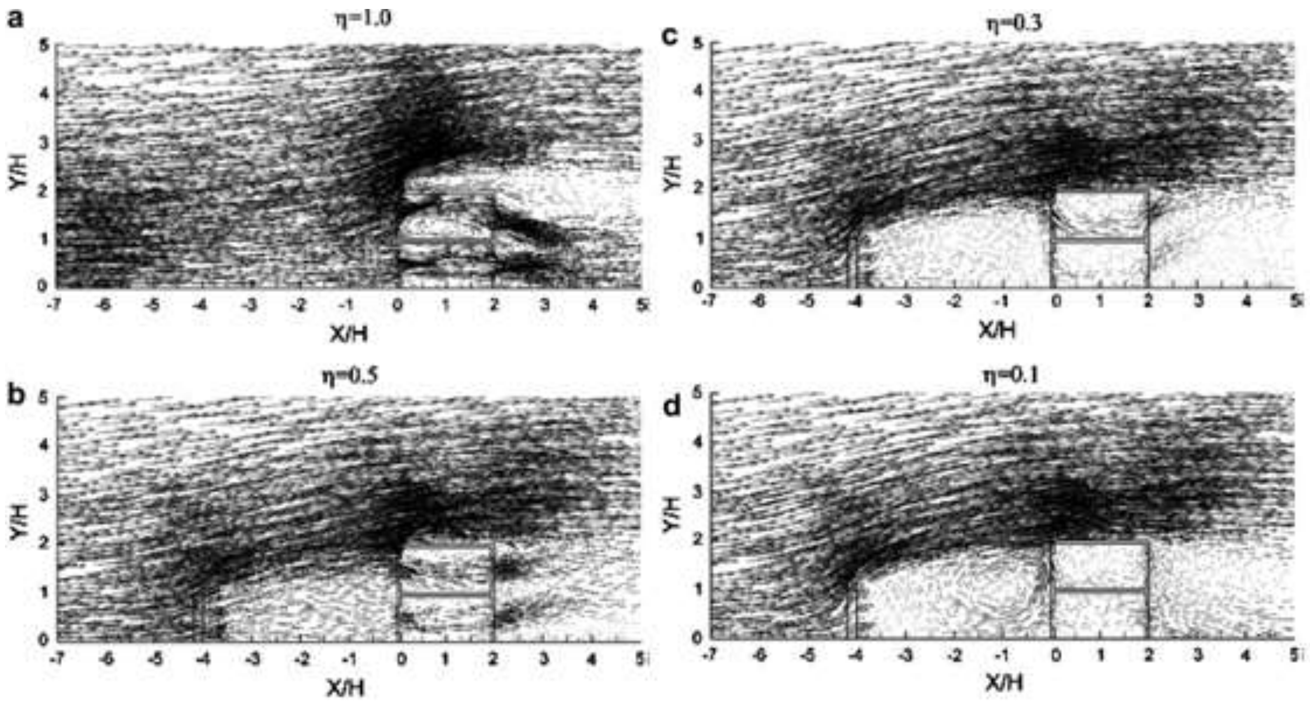

Figure 1 Effect of a porous media on natural ventilation, over high porosity by (a) to less porous (d) [9].

The crop can be modeled accurately as a porous media zone, with air exchange and convection latent heat flux. The effect of plants on greenhouse ventilation has also been studied previously. Bournet et al. [10] assumed that a crop of 90 cm high and low density decreases between 12 and 15% ventilation. Using porous media approach have been obtained realistic models; Dayan et al. [11] conducted a representative model of a greenhouse with three vertical segments, containing plants horizontally oriented to directions of the airflow and vapor transfer between the segments, considering the external environment, which concluded that the representative temperatures plants (RPTs) could be calculated rather than measured. A 3D CFD model for characterizing weather conditions in a greenhouse was developed by Roy and Boulard [12], incorporating five rows of tomatoes crop as a porous media zone, considering the buoyancy, transfers heat and moisture between the crop and the airflow. The heat and moisture transfer coefficients were deduced from the characteristics of the laminar boundary layer sheet, calculated with the speed air in the drop zone. The orientation of the porous media zone determines the climate conditions inside a greenhouse. According to Majdoubiet al. [13, 14], the crop oriented perpendicular to the movement of air; reduce in 50% the rate of ventilation through the crop in a greenhouse. The effect of the crop was evaluated by Impron et al. [15], determining the effects of ventilation, the properties of the cover, and crop transpiration. Stomata resistance, combined with the aerodynamic drag of the blade, allowed to calculate the resistance of the cover in a banana crop, to assess the transfer of water vapor depending on the climate and crop characteristics [16]. The buoyancy and turbulent models are an important component to the porous media of distribution the mass and energy; Sapounas et al. [17] performed a simulated tomato crop using a porous media zone, considering adding buoyancy to develop a model of the pressure drop of airflow due to crop, comparing the RANS turbulence model with the RNG k-ε model. The conditions of the area of porous media can be adjusted by specific functions that simulate physiological processes crop. In a greenhouse tunnel, a tomato crop was modeled by Bartzanas et al. [18] through the design of a porous media, which highlights the influence of the heating system on the microclimate of the greenhouse. Climate behavior in the rows of growing tomatoes could be taken through user-defined functions [19].

Moreover, it is possible to simulate the plants independently, dividing the domain into sub-domains; Endalew et al. [20] conducted a CFD model of a plant with leaves and branches of the cup, using equations of turbulent energy in porous sub-domains created around the branches. The crop can be simulated as a set of layers of porous media, as shown by the work carried out by Fidaros et al. [21] as an alternative way to increase the realism of the model. In general, there have been enormous efforts devoted to the analysis of ventilation in greenhouses [22], each new research brings new elements not only air movement in the greenhouse, but the forms that due to the interactions that occur in environment, such as position, shape, and size of the windows, and one of the most important, the presence of a crop. Configure at 1.0 porous media in crop permits the flow of sufficient air to stabilize the weather conditions. However, CFD models are not allowing us to understand the relationships between the porosity and the volume of the crop with the variables that comprise the climate in natural ventilation greenhouses at the same time.

On the other hand, Bayesian Networks (BN) can be used to identify previously undetermined relationships among variables or to describe and quantify these relationships [23, 24]. Friedman [25] first introduced the Naïve Bayes method for structure learning with incomplete data. This method is based on the Expectation-Maximization principle. Therefore, a porous media CFD model of the crop and its approximations were developed and analyzed through naïve Bayesian EM Networks, with the aim of determining how the density of a crop influences the climate conditions in a natural ventilation greenhouse.

Darcy-Forchheimer theory

The linear relationship between the pressure drop and the average speed volume caused by viscous friction (Darcy law) is not met in high-speed flows, which are often found in the natural environment. A modification of this law has been provided by the equation of Darcy-Forchheimer, which relates the drag force through a porous media to a linear combination of the flow rate, i.e., the viscous resistance due to the limits of obstacles, and the resistance due to inertial effects. This can be described as follows:

$$\frac{\partial p}{\partial x} = -\frac{\mu}{K}\bar{u}_i + \rho\left(\frac{C_F}{\sqrt{K}}\right)\bar{u}_i|\bar{u}_i| \qquad (1)$$

where μ is the dynamic viscosity of the fluid, K the permeability of the porous medium, v the density of the fluid, and CF the non-linear loss coefficient.

Crops such as porous media

The resistance of greenhouse crops has been taken into account in the CFD models by adding as a porous media, which is based on the Darcy-Forchheimer equation. This pulse creates a pressure drop related to the rate of airflow through the porous media [10].

$$S = -\left(\left(\frac{\mu}{K}\right)v + \rho\left(\frac{C_F}{K^{0.5}}\right)v^2\right) \qquad (2)$$

where μ is the dynamic viscosity of the fluid, K permeability porous media, fluid density v, and CF nonlinear coefficient loss.

Materials and Methods

This work was developed in a commercial greenhouse at the Autonomous University of Queretaro, which is located at the geographic coordinates: latitude north 20° 42 ' west longitude 100°16' and altitude of 1920 m. The climate, according to Koppen, is generally classified as semi-dry, semi-arid, with rain in summer and a winter rain smaller percentage of 5. The average annual temperature ranges from 18° to 19° C, the total annual rainfall fluctuates between 450 and 630 mm. This greenhouse is oriented north to south of Gothic type; the dimensions are as follows: 5000 m2 divided into 10 buildings, where every ship is 9 wide, 4.20 m in height to the gutter, 6.70 m to the ridge (2.50 m ridge) and 100 m long. Not only has lateral roof window roller type, 3 x 9 m to the front and back sides and 3 x 16 m to the sides (Figure 2).

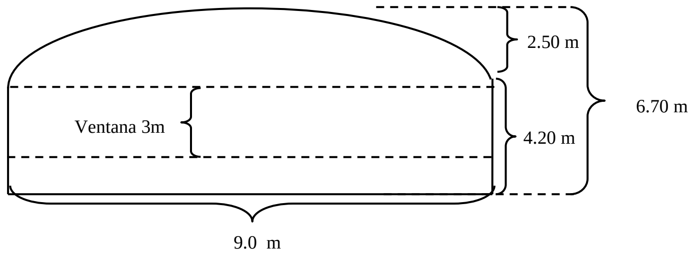

Figure 2 Dimensions of two ships of the commercial greenhouse

Characterization of airflow and state variables

Sampling and measurements of airflow through omnidirectional anemometry were performed. A set of experimental data was obtained in 36 hours ranging from 10 to 11 August 2015, through the use of sensors placed in the central part inside the greenhouse. The data set consists of the variables: air temperature, humidity, wind speed, and CO2 concentration. Measurements were obtained at two levels; one meter within three meters of the crop and soil on the crop.

The temperature and humidity measurements were performed at four-minute intervals by a sensor of type LM335. The CO2 concentration was determined using a carbon dioxide sensor of FYA600CO2H type. The speed and direction of air were determined by omnidirectional anemometers whose operating range is 0 ms-1 to 20 ms-1 with an accuracy of 0.03 ms-1.

The data were discretized by ELVIRA system, as shown later to be used in developing the model of Bayesian networks that describe the relationships between all the variables. Temperature, relative humidity, solar radiation, and CO2 concentration inside the greenhouse: sampling and measurements of state variables were carried out. Similarly, and to establish the climatic conditions of the greenhouse environment, measurements for the same state variables were performed using the weather station TUNA developed at the Autonomous University of Queretaro.

CFD model development

Development model and numerical simulation with CFD software ANSYS v.14 which was executed on a 64-bit PC, Intel Core ™ i7-2600 processor at 3.4 GHz, 8 GB RAM, and were conducted under the Windows 8.1 operating system Professional, whereby energy equations, continuity and time-resolved.

CFD model configuration and solution of equations

The commercial greenhouse was simulated by the CFD model, where the windows as inputs and outputs of the airflow based on the values of speed air previously measured by sensors in the greenhouse are designed. The space occupied by the crop was simulated using 3D elliptical figures and assigning the properties of porous media. The solution of the 3D model was performed by applying the steady-state equations 3, 4, 5, 6, 7 and 8 shown below. Table 1 shows a summary of the boundary conditions and initial values shown.

$$\nabla \equiv i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z} \quad V \equiv (u, v, w) \qquad (3)$$

Continuity equation

$$\frac{\partial}{\partial t}\iiint_V \rho dV + \iint_S \rho V \cdot dS = 0 \qquad \textbf{(4)}$$

Momentum equation

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial t_{xx}}{\partial x} + \frac{\partial t_{yx}}{\partial x} + \frac{\partial t_{zx}}{\partial x} + \rho f_x$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial t_{xy}}{\partial x} + \frac{\partial t_{yy}}{\partial x} + \frac{\partial t_{zy}}{\partial x} + \rho f_y$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial t_{xz}}{\partial x} + \frac{\partial t_{yz}}{\partial x} + \frac{\partial t_{zz}}{\partial x} + \rho f_z \qquad (5)$$

Energy equation

$$\rho \frac{Dw}{Dt}\left(e + \frac{V^2}{2}\right) = \rho q + \frac{\partial}{\partial x}\left(k + \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k + \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k + \frac{\partial T}{\partial z}\right) - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z}$$

$$+ \frac{\partial(ut_{xx})}{\partial x} + \frac{\partial(ut_{yx})}{\partial y} + \frac{\partial(ut_{zx})}{\partial z} + \frac{\partial(vt_{xy})}{\partial x} + \frac{\partial(vt_{yy})}{\partial y} + \frac{\partial(vt_{zy})}{\partial z} + \frac{\partial(wt_{xz})}{\partial x} + \frac{\partial(wt_{yz})}{\partial y} + \frac{\partial(wt_{zz})}{\partial z} + pf \cdot V \qquad (6)$$

Steady equation

$p = \rho RT$ (7)

Specific heat at constant volume equation

$e = CVT$ (8)

Table 1 Summary of the boundary conditions and initial values of the CFD model

	Description	Magnitude
Solver	3D Simulation	
	Double Precision	
Type of model	Steady-state	
Type of mesh	Automatic Patch Conforming/Sweeping	
	The minimum size of the elements	0.15 m
	Number of elements	
		650,801
Viscosity	K-ε with buoyancy (2ecuaciones)	
	C1-Epsilon	
	C2-Epsilon	1.44
		1.92
Energy equation	Active	
Crop simulation	Porous media	0.0, 0.5 and 1.0

Domain inlet	Inlet velocity	0.4 m s^{-1}	
	Kinetic energy Turbulence	1.0 m^2/s^2	
	Dissipation rate Turbulence		
	Air temperature	1.0 m^2/s^2	
	CO_2 Concentration		
	Relative Humidity	27°C	
		0.0004 kg/m^3	
		0.03	
Domain outlet	Outlet pressure	0.0004 kg/m^3	
	Kinetic energy turbulent		
		1.0 m^2/s^2	
		1.0 m^2/s^2	
Solar radiation	Direct Solar radiation	900 w/m^2	
	Diffuse solar radiation	400 w/m^2	
Physical properties of materials			
	Air	Soil	Polyethylene
Density (kg m^3)	1.22	1400	920
Specific heat (J K^{-1} $°K^{-1}$)	1006.43	1738	1900
Thermal conductivity (W m^{-2} $k^{°-1}$)	24.2 e^{-3}	1.5	0.3
Thermal Expansion coefficient $°k^{-1}$	3.389 e^{-3}		
Species transported	CO_2	H_2O vapor	
Thermal conductivity	0.0454 w/m-k	0.0454 w/m-k	
Viscosity	1.72 e-05 kg/m-s	1.72 e-05kg/m-s	
Mass diffusivity	2.88 e-5 kg/m-s	2.88 e-5 kg/m-s	
Thermal diffusion coefficient	-8e-06 t + 6 e-05 kg/m-s	-2.5 e-3 + 0.13 kg/m-s	

Naïve Bayes EM Network model

This is an iterative method, which convergence has been proven by Friedman [25]. It starts from an initial structure and estimates the probability distribution of variables in which data are missing with the EM algorithm. Then it computes the expectation of the score for each graph of the neighborhood and chooses the one which maximizes the score.

Results and Discussion

The results of solving equations corresponded to the value of the field variables at each grid point. The number of plants per unit area influences the airflow distributes heat, humidity, and concentration of gases through the greenhouse. A higher plant density culture behaves as a solid.

We hope to the advantage of configuring 1.0 porous media in crop permits the flow of sufficient air to stabilize the weather conditions. In this way, the conditions inside the greenhouse could be adequate for the optimal development of the crop, because it has more ventilation, low temperatures, adequate CO2 concentration, and rate humidity, compared to a 0 porous zone crop as shown in Figure 3.

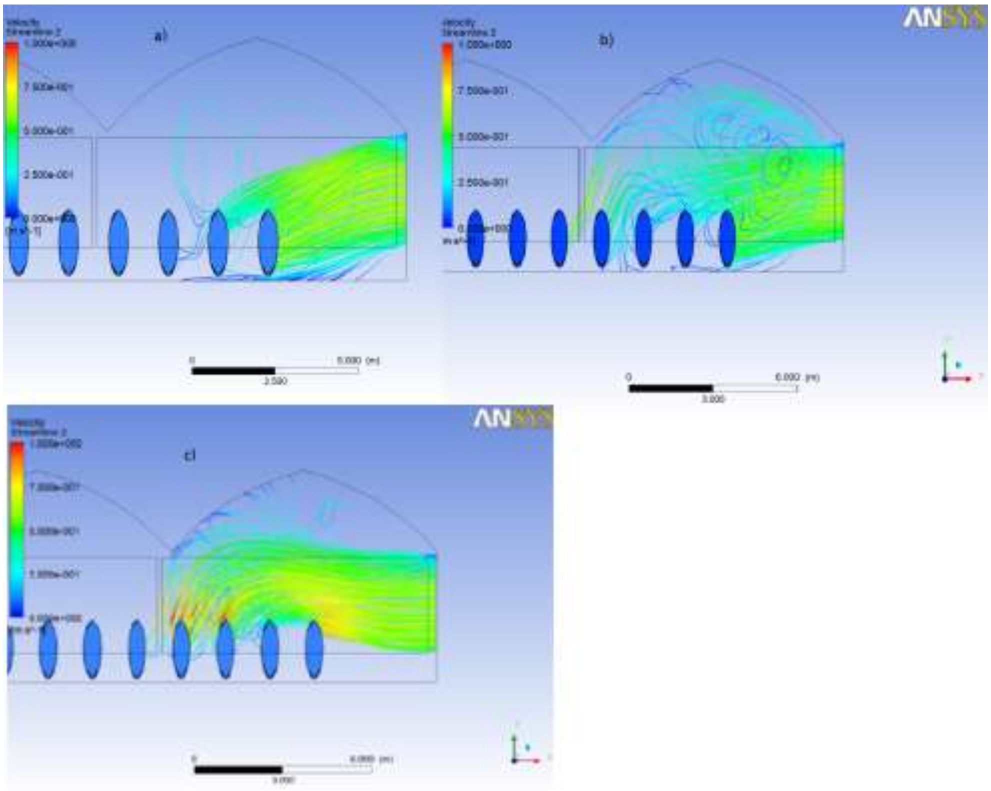

Figure 3 Airflow with a) 0 porous zone crop, and b) 0.5 porous zone crop, and c) 1.0 porous zone crop

The effect of the crop affects the airflow because it forms a barrier that diverts their path; however, this phenomenon increases when the crop is modeled as a porous zone. The presence of a porous region allows the creation of turbulence, having an influence on other variables such as temperature, humidity, and CO2concentration. Temperature is showed in Figure 4.

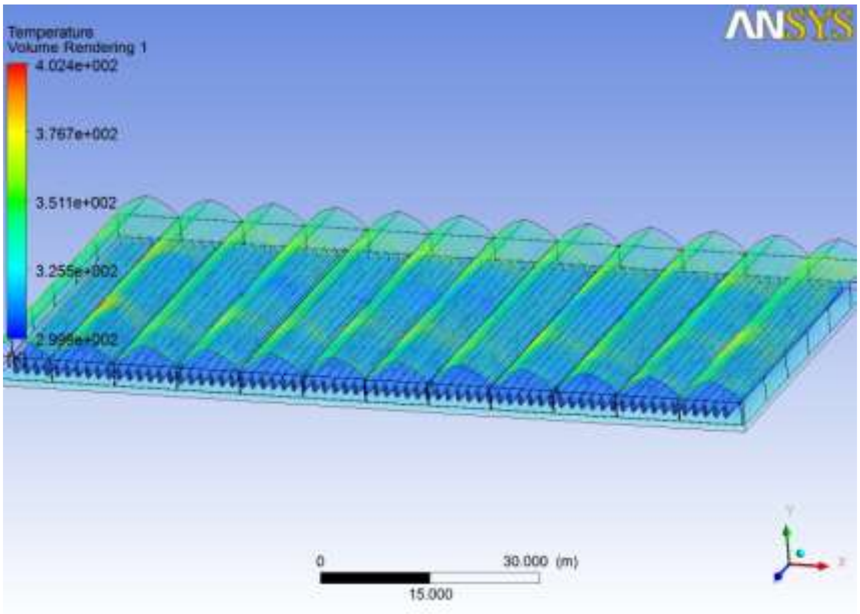

Figure 4. Temperature distribution indoor of the greenhouse.

The real conditions indoor a greenhouse, humidity is determined by the presence of crop, mainly by plant physiology as transpiration allows an atmosphere approaching 100% humidity in a few centimeters of the leaves. However, due to the temperature, the humidity is quickly lost by evaporation (Figure 5).

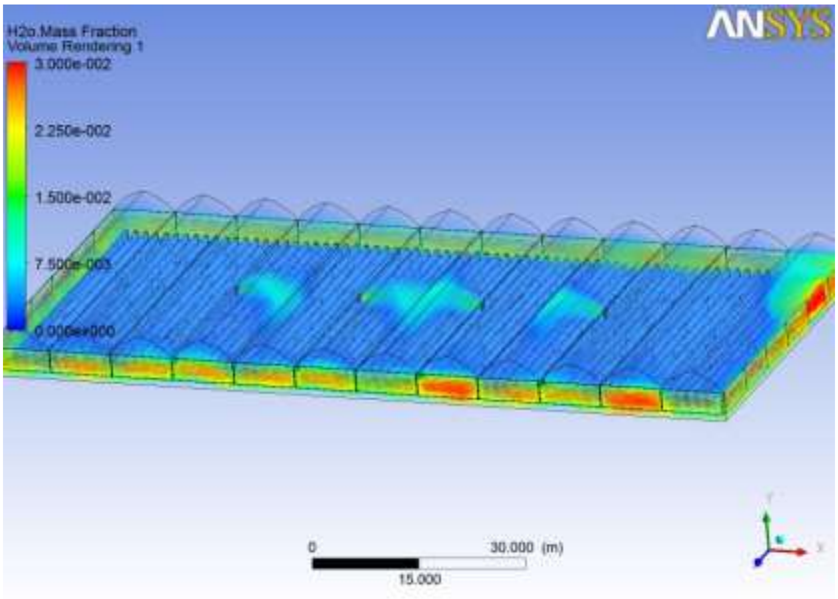

Figure 5. Humidity distributions indoor of the greenhouse.

The CO2 concentration in the greenhouse atmosphere is not influenced by other variables of the system; this is because the inlet airspeed is not enough to move the CO2 from the outside to the center of the greenhouse.Studies that consider the crop are usually to measure the phenomena based on their influence over the development and crop yield. Other investigations established the crop influences to different variables, such as temperature, relative humidity, CO2 concentration, and airflow, where it is necessary to model the space occupied by the crop by using porous media (Fidaros et al ., 2010).

When using porous media in the simulation of the crop in a greenhouse, we have access to configure this medium as a source of species entrained in the air, as humidity and CO2. To simulate a crop as a solid, it behaves like an object that does not let air through it, whereas when it is simulated as a porous medium allows air to pass partially. Thus, a solid not need to be defined by Darcy-Forchheimer law. Moreover, in greenhouse crop, the plants are intertwined and covered with sheets forming barriers that do not allow the passage of air through the foliage, resulting in specific environmental conditions that do not allow the passage of solar radiation and thus higher humidity and CO2 concentration in the air. Solid crop simulation allows more accurate approximation of the environmental conditions inside the greenhouse as shown in Table 2.

Table 2 Environmental conditions inside greenhouse

	CO_2(ppm)	Radiation(w/m2)	H_2O(%)	Temperature(°K)	Speed air(m/s)
Porous media	282.57	1589.77	0.037	301.17	0.19
Solid	305.75	2258.33	0.002	306.54	0.32

Analysis using Bayesian Networks

To analyze the relationship between variables, ELVIRA system v 0.162 in three stages, suggested by Garrote [26] and Ortiz-Vazquez [27] were used:

a) It is carried out using the algorithm of allocation "to mean" to complete the series of partial data. This algorithm replaces lost or unknown values, the mean values for each variable. This method requires no limits and involves discretizing the massive data by the algorithm using two intervals with the same frequency.

b) We developed a naïve Bayes model unsupervised by the EM algorithm, initialized with the Naïve Bayes model with parameters taken at random. The resulting model maximized the likelihood of the training data set.

c) Dependency analysis was performed to get the topological structure of the network, which represents the causal variables and their dependencies. After obtaining a parametric learning network, the conditional probabilities variables that show the relationship or dependence were calculated.

Bayesian Network Model from the CFD model

A Naïves Bayes EM network structure was obtained from 5560 data measurements of temperature (tD), solar radiation (iD), humidity (h2oD), CO2 concentration (co2D), viscosity (eddyD), and wind speed (vD), a CFD model whose inferences is shown in Figure 6.

Figure 6. Naïves Bayes EM Network model using datafromCFDmodel: xD, yD, and zD are the greenhouse dimension: a) porous medium, and b) solid. The model obtained by the naïve Bayes EM algorithm shows the relationships between variables from a class node which link them; applied to the approximation of the porous medium crop in Figure 6a and 6b when the crop is considered a solid, due to its higher density. Porosity is directly influenced by humidity, temperature, and slowly to CO2 concentration. Solar radiation, speed air and slowly the height are inversely influenced with the porosity. Although viscosity is not defined in the model as directly or inversely proportional to porosity when the crop is simulated as solid, viscosity increases to more than double its value. A lower porosity, solar radiation is increased; causing the speed air is growth by the effect of buoyancy but also by the rebound effect with dense culture, consistent with the studies obtained by Majdoubi [14].

Moreover, by increasing the speed air, better ventilation is obtained causing a decrease in temperature, and the humidity is increased, as there is less evaporation. It also shows that the concentration of CO2 is benefited. These relationships between variables imply a probability value, which was calculated with the Bayesian inference and shown in Table 3. The inference probabilities are very important because they allow us to establish the likelihood that the data obtained by approximation using CFD present in reality.

Variable	Porous media crop		Solid crop	
	Value	Probability	Value	Probability
Temperature (°K)	330	0.23	300	0.71
Humidity (%)	0.9	0.99	0.1	0.71
CO_2 (ppm)	200	0.99	200	0.99
Eddy v. (kg/m-s)	0.015	0.22	0.038	0.41
Solar r. (W/m^2)	500	0.99	2360	0.18
Height (m)	2.15	0.3	2.15	0.28
Large (m)	35.6	0.18	18.1	0.19
Speed air (m/s)	0.116	0.3	0.0	0.42

Table 3. Inferences between porous media and solid crop BN model

The probabilities obtained were calculated by Bayesian inference dependent on the porosity of the crop. Thus an equal porosity to zero indicates that the crop is being simulated as a solid, while a porosity equal to 1 indicates that the crop is being simulated as a very porous medium. Temperature is a variable that shows a significant decrease comparing it when the crop is simulated as solid as a porous medium, which corresponds to a directly proportional relationship, that is: the lower porosity, the lower the temperature, and a Conditional probability of 71%, which is the main indication that when the density of a crop is sufficiently high that the crop behaves like a physical barrier and gets low temperatures inside the greenhouse. As a direct consequence of reducing the temperature inside the greenhouse, humidity is kept at 71% probability, by a decrease in evaporation of perspiration independently exerted by the crop. On the other hand, the speed air and viscosity will increase with a probability of 42% and 41%, respectively, under the conditions stated above, since the crop simulated as solid momentum conservation prevents frictional drag, produced when the crop is simulated as a porous medium by Darcy-Forchheimer theory. According to the calculation of Bayesian inference, the best environmental conditions under the greenhouse culture studies are presented at the height of 2.15 m, and 26 m in length on the central plane of the greenhouse; at this location lower temperature and higher humidity were observed, solar radiation and adequateCO2 concentration, with high crop density.

Conclusions

Temperature is a variable that shows a significant decrease comparing it when the crop is simulated as a solid, and its probability of decrease is 71% dependent zero porosity. When the density of a crop is high as a physical barrier, the temperature will drop inside the greenhouse. Porosity is directly influenced to humidity and slowly to CO2 concentration. Solar radiation, speed air, and slowly the height is inversely influenced by the porosity. Naïve Bayes EM application to a CFD model has been providing a greater understanding of the interactions between the variables that make up the climate inside greenhouses.

Acknowledgments

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Nomenclature

Cv	Specific heat
R	Specific gas constant
T	Temperature
p	Pressure
e	Energy
J	Joule
m	Meter

W	Watt
K-ε	Turbulence model
CO2	Carbone dioxide concentration
xD	Cartesian axis to define the dimensions of the glasshouse in meters
yD	Cartesian axis to define the dimensions of the glasshouse in meters
zD	Cartesian axis to define the dimensions of the glasshouse in meters
TD	Temperature
°C	degrees Celsius
°K	degrees Kelvin
h2oD	Humidity
vD	wind speed
iD	solar radiation