Development of a User Friendly Application for the Simulation and Design of Greenhouse Environments

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ABSTRACT

This study presents an application to simulate the internal temperature and relative humidity of a greenhouse, which provides a simple way to predict crop environmental requirements. Programming was developed in a worksheet with subroutines based on a steady model of energy and mass transfer and as well as psychometric relationships. It contains a user friendly interface that helps increase the analysis and design capabilities on greenhouse environments in countries with low-tech possibilities. This tool can help professionals involved in the greenhouse industry to better understand the complexity and behavior of a greenhouse environment. It can be used as a support aid to evaluate the crop´s specific sustainability in a greenhouse given climate conditions and it can also help design the mechanical systems in order to improve crop productivity. Additionally, in existing projects, this tool can be used to evaluate mechanical systems and a variety of devices that could provide optimal conditions for a crop improving investment efficiency. Implementing this method demonstrated in several validation studies carried out in Costa Rica, that it is possible to achieve suitable precision in the simulation and design of greenhouse environments using basic computational resources.

Keywords: Simulation, steady modeling, energy balance, protected environments, climate control, Costa Rica.

1. INTRODUCTION

Protected environment production has been acknowledged as an alternative that increases crops yields, allows good harvest program controls, helps in the reduction of agrochemical use, and permits an efficient use of irrigation, decreasing water consumption compare to open field agriculture. Nevertheless, it has an implicit higher cost in initial investment and installation maintenance. Greenhouse production should aim optimization of environmental conditions required by the crop in all its production cycle. Proper internal temperature, relative humidity, light conditions, radiation, allows crops to improve foliar and flowering development as well as its productivity (Tesi, 2001).

Costa Rica doesn't have a greenhouse crop operation plan, which hinders crop management throughout its cycle. There is an absence of technical support caused by lack of experience in the field of study (Barquero, 2001). The 2008 census made by Costa Rican National Protected Environment Program (ProNAP), which surveyed 688 Hectares of protected agriculture, states that only 2.04% of the analyzed production units record weather variables and 12.26% use thermometers. Low percentages of weather data registration indicates the small amount of technology that is applied in the country in protected production systems. These systems can be categorized in two levels: traditional and formal construction.

Traditional systems involve practices similar to the ones use in open field agriculture, which is considered to be an underutilization of the structures. There is a lack of climatic and pest management knowledge that prevents the structure to be used to its full investment potential. Design or analysis of crop environment are absent in this systems and there is rarely a record or description of weather conditions.

Formal systems involve projects develop by divisions of foreign companies that design and built structures with high levels of technology, involving thermal and structural analysis. Users of this kind of systems often are groups of farmers or companies that have abundant financial resources. It has been observed that in some projects, automation is disabled and weather stations, included in the system, haven't been installed. This suggests that weather management in formal systems is not operated correctly due to lack of understanding of the users and degree of technical difficulty.

Farmers that use protected production systems rely in the administration of the climate parameters to obtain "optimal" conditions for their crops. A proper design of the structure or an adequate automation program can be achieve by learning and understanding relations between the factors that constitute internal climate. Mathematical models can be used to explain these relations.

Several greenhouse models, based on energy and mass equations have been investigated in the past, such as Castañeda (2003), used to develop a climatic control system, Leal, J et Pissani, J.F. (2010), which modeled internal climate inside a greenhouse in Mexico, López (2004), that simulates internal temperature of a greenhouse and Leal et Costa (2004), which performed a simulation of internal relative humidity and temperature of a greenhouse in Brazil. This kind of models can be classified in static and dynamic models. Refined and more complete greenhouse environment models currently exist, however they are too complicated to be used for an easy application to predict the internal climate of greenhouses. The simplified static greenhouse environment model, based on energy and mass balance equations follows the models of Albright (1990), Hellickson (1983) and Leal (2011).

This study presents an application to simulate the internal temperature and relative humidity of a natural ventilated greenhouse, which provides a simple way to predict crop environmental requirements. An application that simulates the internal environment of a greenhouse could enable the operator to take accurate decisions in climatic administration; it can predict the time intervals in witch crops will be in stress due to temperature and relative humidity. This tool can help design inlet sizes for natural ventilation systems and to have an idea on the requirement and implementation of mechanical systems.

2. MATERIALS AND METHODS

This study was developed as part of a thesis in the University of Costa Rica Agricultural Engineering School which consists of the validation of a mathematical model to predict internal conditions of a greenhouse in Costa Rica. The thesis includes: analysis of the spatial differences in temperature and relative humidity inside the greenhouse, simulation and validation of the mathematical model, and developing an application that can be used to simulate internal temperature and humidity. The application is based on a mathematical model program on a workbook in Microsoft Excel. This workbook includes several macros programed using Visual Basic for Applications (VBA), psychrometric relations and potential evapotranspiration calculations and the mathematical model representing the physics of the greenhouse environment.

The application was used and validated in two different locations of the country, Cartago (N 09°53′02.5”, W 083°53′52.1”), at 1638 AMSL in the greenhouse used to fulfilled the thesis objectives and at the Fabio Baudrit Moreno Experimental Station greenhouse, in Alajuela (10° 0’22,89”N, 84°15’54,63”W), at 840 AMSL. In the first case, climatic data was obtained using a Vantage Pro2 Plus™ weather station, and the experimental period was between June 8 and July 18 of 2011 (41 days). In the second case, climatic data was obtained from the National Meteorological Institute (IMN), and two experimental periods were used due to validation information: from the month December 2009 and between August 10 and October 19 of 2010

2.1 Climatic Data

Climatic data form the two geographic locations were used to provide the outside environmental conditions as inputs to simulations. The five climatic parameters necessary to simulate conditions inside the greenhouse are: temperature, relative humidity, radiation, wind speed and wind direction. These were documented for each site in the time periods mention. Hourly averages of the parameters were used to run the simulation. Predominant wind direction was determined for each location.

2.2 Greenhouse Components

Greenhouse structural components and their geometry affect both solar radiation transmission and heat transfer by conduction. This heat fluxes change due to the differences in floor and glazing area. Both greenhouses were Arch-roof, which is widely used in production systems. Glazing material used in both simulations was single layer polyethylene film; however, its optical properties were different due to aging of the material. Other parameters needed in the simulation for both greenhouses are indicated in table 1. Dimensions of the greenhouses and inlet areas were measured in situ.

Table 1. Dimensions and properties of greenhouse designs used in the simulations.

Greenhouse Data	Cartago Greenhouse	Alajuela Greenhouse
Altitude (AMSL)	1638	840
Number of modules	4	4
Length (m)	45	55
Module width (m)	9,6	9,6
Arch area (m2)	13,23	13,30
Arc length (m)	10,68	10,70
Gutter high (m)	4	4
Ridge high (m)	6	6,5
Curtain shadow (%)	50	0
Perimeter (m)	166,8	186,8
Glazing area: Ac (m2)	2415	2352
Internal air specific heat (J/kg*K)	1002*	1002*
Floor Area (m2)	1728	2112
Inlet size Aa: (m2)	82,32	206,9
Glazing properties		
Short wave transmittance	0,79**	0,8***
Long wave transmittance	0,32**	0,75***
Global heat transmission coefficient: U (W/m2C)	7,14	7,14

*: Value suggested by Leal (2011).
**: Photonic and Applied Laser Technology Laboratory of the University of Costa Rica (LAFTA).
***Glazing company, Olefinas de Costa Rica S.A.

2.3 Mathematical model

The mathematical model described the state of the greenhouse environment and consists of 11 equations which were obtained from energy and mass balance principles. Solving the equations will result in internal temperature and relative humidity of the greenhouse. As it is assumed that ambient temperature is below the greenhouse temperature, the thermal balance can be written as:

$$Q_{so} + Q_{resp} + Q_{ve} = Q_{fot} + Q_{ce} + Q_{sp} + Q_{sl} + Q_{vs} + Q_{tt}$$

Where:
Q_{so}: Solar heat input, W.
Q_{fot}: Heat of photosynthesis, W.
Q_{resp}: Heat of crop respiration, W.
Q_{ve}: Heat of ventilation gain, W.
Q_{ce}: Conduction heat loss or gain, W.
Q_{sp}: Conduction heat loss or gain to the ground, W.
Q_{sl}: Sensible heat converted to latent heat, W.
Q_{vs}: Heat of ventilation loss, W.
Q_{tt}: Thermal radiation heat, W.

Each term (figure 1) can be defined by which allows quantification of the term under given condition, for example, the solar heat input (Q_{so}) can be defined by:

$$Q_{so} = \tau_c \times S_l \times I_s \times A_p$$

Where:
τ_c: Short wave transmittance. (Adimensional)
S_l: Curtain shadow (decimal).
I_s: Solar radiation, W/m^2.
A_p: Floor area, m^2.

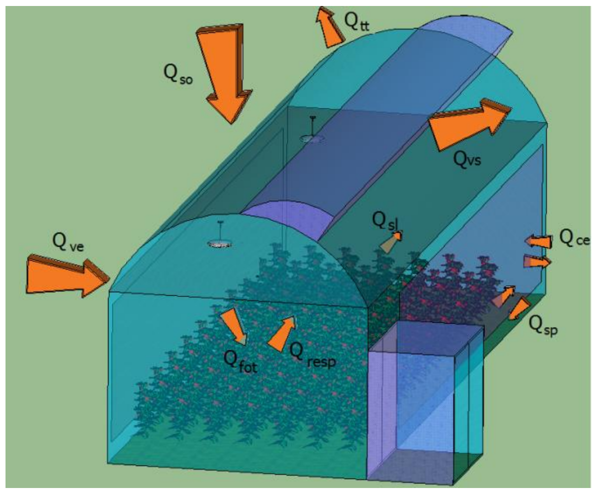


Figure 1. Energy losses and gains in a ventilated greenhouse.

Mass balance is used to determined humidity levels in a ventilated greenhouse; this balance is similar to the thermal balance, since there is no moisture transmission through the glazing, it is much simpler. The mass balance can be calculated by:

$$\dot{M}_{aev} = \dot{M}_{ve}$$

Where:
$\dot{M}_{aev}$= Moisture added to the greenhouse environment by evapotranspiration. kg/s.
$\dot{M}_{ve}$= Moisture exchange in the ventilation air. kg/s

Moisture exchange in the ventilation air can be obtained by multiplying the difference between interior and exterior humidity ratio and the air flow rate of the greenhouse. Details of how to calculate other thermal and mass balance equations used on the simulation can be found in Albright (1990), Hellickson (1983), Leal (2011), and López (2013).

2.4 Functionality and subroutines of the application

Equations for obtaining psychrometric relations and potential evapotranspiration were included in the application, allowing automatic calculations for parameters needed in the mathematical model such as air density, local emissivity and internal absolute humidity among others. Details of the equations programed can be found in López (2013), ASAE (2004), Leal (2011), Brooker (1981), FAO (2002), and FAO (2006).

The interfase of the program allows the user to choose between two solving modules programed via VBA macros. The independent module outputs results for one package of input data. A package of data is defined by the temperature (°C), relative humidity (%), solar radiation (W/m^2), wind speed (m/s), and wind direction (one of 8 preprogram directions) attached to a time unit (hour, day, or month). This allows the user to change any of the parameters involved in the model for that determined time unit. Inputs for this module must be entered directly in the Model spreadsheet

The batch module allows the user to calculate results for several packages of data. This module can calculate results for series of hours, days or months. It also allows you to display the results in a form of a table in a different spreadsheet. Results include simulated internal temperature (°C) and relative humidity (%) and values for each of the heats involve in the model in watts. Also, the user can input measure internal climatic values and the program calculates differences between measured and simulated values. Inputs for this module must be entered in the Filter spreadsheet, where a filter can be used to choose the preferred interval to analyze.

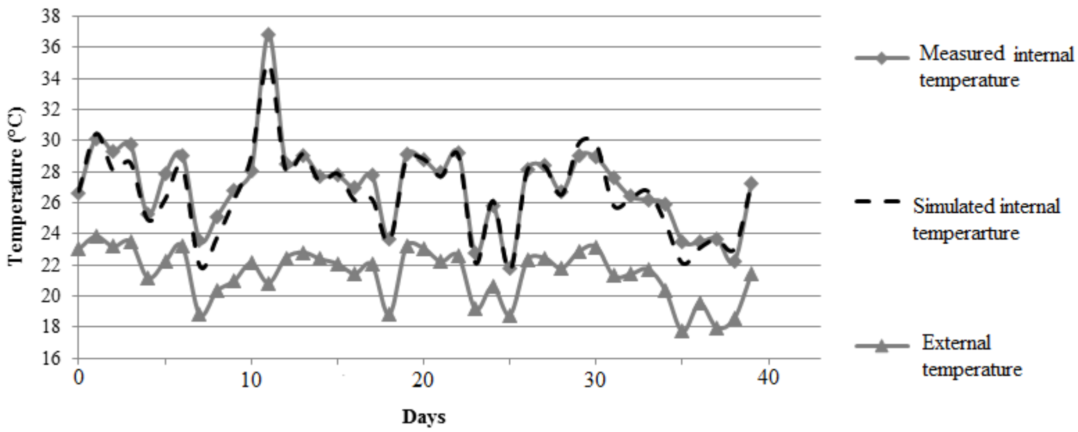
The application has programed checkboxes that allows the user to choose witch heats of the mathematical model are participating in the solution of the equation. This allows the user to observe and analyze the impact that each of the different parts of the equation have on the results.

3. RESULTS AND DISCUSSION

The batch module was used to simulate internal temperature and relative humidity in the greenhouses using as inputs the obtained and processed climatic data and values of table 1. In the periods of time that were analyzed, some days the greenhouse would operate in an unexpected manner due to problems in electrical systems or loss of communication with control systems, in this cases, the independent module was used to change certain parameters according to those operational schemes. To evaluate and validate the application performance, simulation results were later compared to measure climatic data inside the greenhouse.

3.1 Validation of the model and analysis of application performance

Average differences between series of simulate temperature and measured data were lower than 0.64°C with a standard deviation of 0.56°C (figure 2) for intervals where Cartago greenhouse was ventilated. The root-mean-square error (RMSE) in this case was 3.14. Average differences in relative humidity were 2.81% and a RMSE of 5.73. The application cannot calculate intervals when greenhouse is not ventilated due to a change in the model scheme. Detail information about this study can be found in López (2013).



Source: Lopez, (2013)

Figure 2. Measured and simulated temperatures for ventilated greenhouse in Cartago

For Alajuela greenhouse only simulated and measured temperature was compared. Results generated a relative RMSE of 2.99 and 4.69 for the simulated temperature in two different intervals analyzed. Detail information about this study can be found in López et Benavides (2014). Leal et Costa (2004) reports differences between simulated and observed data of 0.64°C witch are comparable with the results of these studies. The RMSE values also indicate good model performance. Vanthoor (2011) reports RMSE values between 3 and 8 on ten different locations for abilities of a model to describe air temperature.

3.2 Limitations of the application

The application only performs for Arch-roof natural ventilated greenhouses. It applies a static model; input data needs to be process thoroughly to avoid incorrect results. To calculate flow through the inlet, wind direction can only be entered in 8 different preset directions. Simulated relative humidity results are inconsistent when wind velocities approach 0. In situations of high relative humidity with internal and external temperatures similar, results are inadequate due to model assumptions.

3.3 Importance and further development

This application can help professionals involved in the greenhouse industry to better understand the complexity and behavior of a greenhouse environment. It can be used as a support aid to evaluate the crop´s specific sustainability in a greenhouse given climate conditions and it can also help design the mechanical systems in order to improve crop productivity. Additionally, in existing projects, this tool can be used to evaluate mechanical systems and a variety of devices that could provide optimal conditions for a crop improving investment efficiency. Implementing this method demonstrated in several validation studies carried out in Costa Rica, that it is possible to achieve suitable precision in the simulation and design of greenhouse environments using basic computational resources. Further development must be encouraged to add versatility to this application. Incorporating subroutines to calculate different greenhouse geometries, worksheets with mechanical ventilation, heating, and evaporative cooling calculations amongst others are essential to improve the program capabilities and can enable users a powerful but simple tool for analysis and design.

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