Development of a Greenhouse Model with an Intelligent Indoor Environment and Energy Management System for Greenhouses

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Abstract:

The microclimate control in a greenhouse is a difficult and complicated procedure since the factors that modulate the clime are several and dependant of each other. This work is an effort of controlling the most of these factors with a conjunction of the most possible low energy consumption. A microclimate system control is designed based on Artificial Intelligence techniques. Two Fuzzy logic controllers are developed embodies the expert knowledge of the agriculturists and the growers. These controllers consist of fuzzy P (Proportional) and PD (Proportional-Derivative) control using desired clime set points. The factors that being monitored are the greenhouse's indoor luminance value, temperature, relative humidity, CO2 concentration and the outside temperature, actuating in automations as heating units, motor-controlled windows, motor controlled shading curtains, artificial lighting, CO2 enrichment bottles and water fogging valves. These controllers obtain the best possible microclimate for any cultivation setting the desired parameters into the set-points. They prototyped in Matlab environment and tested through a greenhouse Model, which was designed into TRNSYS IISIBAT software. For the Model an algorithm developed predicting ambient greenhouse air conditions to be used for energy efficiency simulation and control schemes optimization. The climatic conditions considered are temperature, relative humidity, CO_2 concentration and solar radiation. The algorithm has two modes of operation, the first simulates the greenhouse while in the second the heating, cooling, humidification or dehumidification, CO_2 injection rates are calculated to maintain certain set points. The algorithm is designed to be used with the TRNSYS 15 simulation software which provides the pre-processing of the weather data, as well as controller models. The model is defined by several components that describe the characteristics of each glazing surface, the plants, the floor, the equipment and the zone itself. Using this approach it is possible to simulate any greenhouse structure, provided that the required information is available.

Keywords: Microclimate; Clime factors; Fuzzy logic; Energy consumption; Greenhouse model;

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1. Introduction

The energy saving nowadays is a critical matter that has lead to a trend of designing systems considering the energy usage. This trend is sanctioned in the buildings using known automation protocols such us EIBUS, Profibus, LON, etc. Energy saving in greenhouses is also critical because the energy consumption in such structures is significant, especially in cold climates. The most important thing is to balance the use of the appropriate actuators with the desired microclimate result. Furthermore an important thing is to design a simple but quite efficient system that with low cost can be used in any cultivation. This system uses the most common actuators in order to control the most significant factors that are carried out above the ground of the plant and compose the greenhouse microclimate.

2. The microclimate factors

The growth and production of a plant depends from the lot its hereditary characteristics, meaning the species and the variety or the hybrid, as well as from the environment in which it will be grown. Saying environment is meant all the natural values that affect the growth of plants. The factors of environment that influence decisive the growth and production of plants in the greenhouse can be separated in two teams [1]:

a) The factors that influence the operations of plant, that are carried out in it's part above the ground and are mainly the radiation, the heat, the humidity and the Carbon dioxide.
b) The factors that influence the operations of plant that are carried out in the root and are mainly the heat, the water, the oxygen, the inorganic nutritious elements and the PH.

3. The fuzzy controller

The fuzzy controller is separated in two controllers for design simplicity. The first Fuzzy controller (Figure 1) is a P (Proportional) and PD (Proportional-Derivative) depending the input. The first fuzzy controller (FLC-1) aims to control the concentration of the CO_2 concentration and the radiation inside a greenhouse using actuators such us: CO_2 enrichment bottles, shading curtains and artificial lighting. The inputs of the fuzzy controller are the CO_2 Δerror, CO_2 error and luminance error. In the set points are placed the desired values of the CO_2 concentration and the luminance in order to be achieved into the greenhouse.

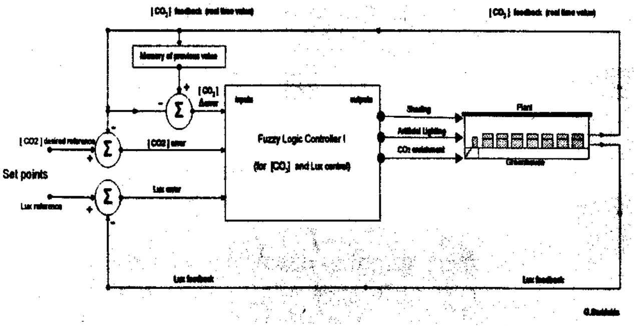

Figure 1.The FLC-1

In the P-part of the fuzzy controller the lux feedback value (real time value) is sent by the luminance sensor from the inside of the greenhouse. The real time value is abstracted from the desired value (set point). The result is been forwarded into the controller input. If the result is positive then it means that the measured value is below the set-point. In parallel if the result is negative it means that the measured value is above the set point.

Eventually $e(k)=y_{sp}-y(k)$ where e(k) is the error, the y_{sp} is the desired reference and the y(k) the output of the system. In the PD –part of the controller the same sequence happens plus the Derivative part. Similarly the real time value of the measured CO_2 concentration is also abstracted from the set point for the desired value.

The change of error Δe(k) shows the kind of rate that a measured value has. The Δe(k) is specified as: $\Delta e(k)=e(k)-e(k-1)$ since $\Delta e(k)=-(y(k)-y(k-1))$ so $\Delta e(k)=y(k-1)-y(k)$, where the y(k-1) is the previous value and the y(k) the real time value. It is obvious that if $\Delta e(k)>0$ then there is a decreasing of the measured value and when $\Delta e(k)<0$ an increase [3]. The Δe(k)of the CO_2 concentration as well as the e(k) are the other two inputs of the controller.

For the luminance control were introduced five membership functions for the input error (Very Negative, Negative, Zero, Positive and Very Positive). The output membership functions of the shading curtains are set as Unshaded, halfshaded and Fullshaded in order to obtain the nessecary shading in the situations of high solar radiation.

The output of the artificial lighting output has two membership functions (on-off). The purpose for that lighting is to add more luminance when the measured value of the luminance is above the Zero region which that means that the value is below the set-point.

The second fuzzy controller has the same logic with the first one. It also consists of one P and one PD controller. The FLC-2 (Figure 2) tries to obtain the desired temperature and the humidity in the interior of the greenhouse using automations as heaters, windows and water-fogging units. In the set points can be placed the desired references that a grower wants to certain cultivations. The internal temperature, the Relative humidity can be set through these set-points. The inputs of the controller are the internal temperature error (T_{in} error), the change of the error (T_{in} Δerror), the outside temperature (T_{out}) and the RH error.

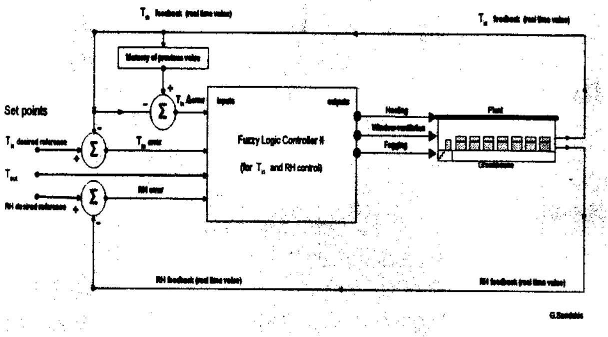

Figure 2.The FLC-2

Three membership functions in all of the four inputs are assigned as Negative, Zero, Positive. The outputs membership functions shapes are trapezoidal and triangular for calculations simplicity without affecting the controllers performance [2][3][4]. The heating output is bearing in mind the inside temperature the rate of the change of the temperature and the outside temperature and is operated when it is necessary. The windows action is influenced by the usage of the heaters the outside temperature and the Relative humidity. The fogging is used according the inside temperature the change of rate of the temperature, the outside temperature and the relative humidity. In order to populate the rule base, a wide literature was studied ([5]-[11]) The FLC-2 consists of 81 rules.

4. The development of the fuzzy controller

The fuzzy controller has been merged into a LON node. Lonworks is a modern automation protocol. The advantage of programmed the fuzzy controller into a separate LON Node is that it takes the benefits of a well defined standarized automation protocol. Any changes or corrections can be achived in the less possible time without the corruption of the control procedure. Furthermore it is easy to collect the measurements data through standarized data loggers. The monitoring, as well as the maintenance of the greenhouse's installation can be done through internet LONWorks network.

5. Model, simulation and results

The introduction of humidifiers, CO_2 injection units, heating/cooling systems as well as modern measuring equipment to crop producing greenhouses has increased the need for the development of highly optimized control systems. In most cases these control systems need to be tested in simulated environments before they are embedded in real greenhouses due to cost issues. Specifically to accurately test a control scheme in a real greenhouse several measurements will be needed over a long time period during which the production of the greenhouse will be compromised. Therefore the need arises for the development of a crop-producing greenhouse simulator.

5.1 Mathematical description

The mathematical description of a greenhouse can be defined by three balances, namely heat, humidity and CO_2.

5.1.1 Heat balance

The heat balance inside the greenhouse is given by Eq. (1). It is a function of the heat fluxes due to convection between the zone air and the glazing surfaces (2), the floor (3), the equipment (4) and the plants (5), the heat fluxes due to infiltration (6) and ventilation (7) and the radiative gains and any other gains due to heating equipment, people, lights etc. For more detailed analysis see [15]. The mass flow rate due to infiltration is calculated by Eq.(8),[16] using empirical constants that depend on the building's construction parameters.

$$\rho_{air}\cdot V_z\cdot C_z\frac{dT_z}{dt}=q_{gl}+q_{fl}+q_{em}+q_{pl}+q_{fv}+q_{\text{in}}+q_{rd}+q_{mc} \quad (1)$$

$$q_{gl}=A_{gl}h_{gl,z}(T_{gl}-T_z) \quad (2)$$

$$q_{fl}=A_{fl}h_{fl,z}(T_{fl}-T_z) \quad (3)$$

$$q_{em}=A_{em}h_{em,z}(T_{em}-T_z) \quad (4)$$

$$q_{pl}=A_{pl}h_{pl,z}(T_{pl}-T_z) \quad (5)$$

$$q_{\text{in}}=\dot{m}_{\text{in}}C_z(T_a-T_z) \quad (6)$$

$$q_{fv}=\dot{m}_{fv}C_z(T_{fv}-T_z) \quad (7)$$

$$\dot{m}_{\text{in}}=\rho_{air}V_z(K_1+K_2|T_z-T_a|+K_3 WS) \quad (8)$$

In order to solve the heat balance, we need to calculate first the surface temperatures of the floor, the equipment, the plants and the glazing, using the respective heat balances on each surface.

The heat balance of the floor (9), describes the floor temperature as a function of the absorbed radiation, the heat flux through its mass towards the underground (10) and the heat exchange with the zone air (3).

$$C_{fl}\frac{dT_{fl}}{dt}=q_{rd}+q_{ug}-q_{fl} \quad (9)$$

$$q_{ug}=A_{fl}h_{fl,ug}(T_{ug}-T_{fl}) \quad (10)$$

Plant temperature (11) depends on the absorbed radiation, heat flux due to the temperature differential between the zone air and the plant and the heat flux due to plant transpiration. The transpiration rate (12) can be described in two forms based on the available information [12].

$$C_{pl}\frac{dT_{pl}}{dt}=q_{rd}-q_{pl}-\lambda E_{tr} \quad (11)$$

$$\begin{aligned} E_{tr}&=k_1 I_{tot}+k_2(e_{sat}-e_z) \\ E_{tr}&=\frac{k_1}{\lambda}\ln(1+k_2 LAI^{k_3})I_{tot}+\frac{k_4}{\lambda\gamma}(1-k_5 e^{-I_{tot}/k_6})LAI(e_{sat}-e_z) \end{aligned} \quad (12)$$

The temperature of the equipment is a function of the absorbed radiation and the heat exchange with the zone air and is described by Eq.(13).

$$C_{em}\frac{dT_{em}}{dt}=q_{rd}-q_{em} \quad (13)$$

The heat balance of each glazing surface (14) is equal to the sum of the heat flux to the outside through the glass mass, the flux by convection with the inside air and the radiative gains. The heat flux to the outside (15) is the sum of the conduction through the glass mass, the convection with the outside air and the radiative heat loss to the sky.

$$C_{gl}\frac{dT_{gl}}{dt}=q_o-q_{gl}+q_{rd} \quad (14)$$

5.1.2 CO$_2$ balance

The state of the CO$_2$ inside a greenhouse is defined by Eq.(20) and depends on the CO$_2$ injection rate, the CO$_2$ loss due to ventilation and infiltration (21) the respiratory CO$_2$ production (22) and the photosynthetic CO$_2$ consumption rate (23) [15].

$$\frac{dc_z}{dt}=CD_{mc}+CD_{in}+CD_{rs}-CD_{ps} \quad (16)$$

$$CD_{in}=\frac{\dot{m}_{in}+\dot{m}_{fv}}{A_z}(c_a-c_z) \quad (17)$$

$$CD_{ps}=\frac{\phi I_{ps} g_s c_z}{\phi I_{ps}+g_s c_z}[1-k_1(T_r-T_z)^2] \quad (18)$$

$$CD_{rs}=W R_r e^{k_2(T_z-T_r)} \quad (19)$$

5.2 The TRNSYS model

The TRNSYS simulation environment allows complex models to be formulated by interconnecting smaller models or units. For the simulation of a greenhouse the user will need at least a data reader unit to read the weather information from a file, a radiation processing unit that provides the beam, diffuse and angle of incidence of the solar radiation on each surface and a printing or plotting unit in addition to the greenhouse unit. An example of such a model is shown in Figure 3.

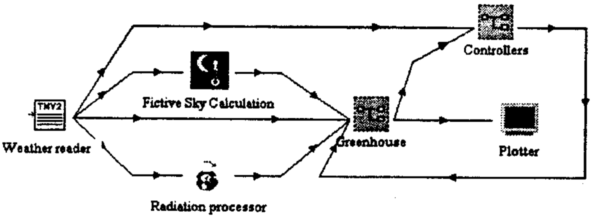

Figure 3. The greenhouse model using TRNSYS software

Because of the large number of parameters, inputs and outputs needed to define the greenhouse unit (they may easily exceed 300), the model is divided into several components that each describes a part of the model. The zone component is obligatory; it defines the main characteristics of the greenhouse and provides the outputs. There are also components for the floor, the equipment and the plants (only one of each allowed). Through repeated use of the glazing component all the glazing surfaces can be described. The user is also obligated to include one geometry component that includes the view factors between the surfaces for radiative transfer calculations and optionally the additional outputs component that provides additional outputs to the standard of the zone component.

5.2.1 Zone component

The zone component is the main component of the model and provides a description of the general characteristics of the greenhouse air zone. There are two modes for the zone component, temperature level control and energy level control. In the second mode the temperature, humidity and CO_2 are kept constant at a given setpoint and the heating, humidification and CO_2 injection demands are calculated.

5.2.2 Glazing component

To model the whole glazing of the greenhouse the user makes use of repeated glazing components, each of which is used to model an individual surface. Each component must be assigned a surface number from 1 to the number of glazing surfaces defined in the zone component.

5.2.3 Plants component

There are two ways to model the plants inside the greenhouse. The first method calculates internally the heat, moisture and CO_2 exchange between the plants and zone, while in the second method these are input to the model. The plant component is configured to allow the use of any of the two methods individually for the heat, latent heat and CO_2 gains. Thus we are able to calculate the heat flux internally and use an outside more detailed component for the calculation of the other gains.

5.2.4 Floor component

There are two ways to model the heat flux through the floor of the greenhouse. The first mode assumes a standard conduction resistance with known surface temperature on the other side, while the second a constant heat flux leaving the zone.

5.2.5 Equipment component

The equipment component is used to model the effect of the cladding, tanks and other equipment present in the greenhouse by considering them as a lumped system modelled by a single surface.

5.2.6 Zone geometry component

This component is used to store the view factors between all the surfaces. Since the surface areas are known the user needs to specify only the i,j where i<j and the rest are computed internally.

5.3 Model testing

The model was tested by simulating a real greenhouse operated by the Mediterranean Agricultural Institute of Chania (MAICh) that is situated inside the MAICh complex in Souda, Chania, Greece (24.15E, 35.53N). The basic characteristics of the greenhouse are summarized in the Table 1.

Table 1. The characteristics of the greenhouse

Greenhouse area	: 160 m^2
Greenhouse volume	: 560 m^3
Number of glazing surfaces	: 12
Glazing material	: Glass

It should be noted also that the floor does not border with soil, since there is another zone beneath the greenhouse which houses the pumping station, the measuring station and other equipment. Table2 that follows summarizes the geometrical characteristics of the glazing surfaces.

Table2. The geometrical characteristics of the greenhouse's glazing surfaces

	1	2	3	4	5	6	7	8	9	10	11	12
Area (m^2)	38.1	45.5	38.1	45.5	22.3	22.3	22.3	22.3	22.3	22.3	22.3	22.3
Azimuth	-90	0	90	0	-90	90	-90	90	-90	90	-90	90
Slope	90	90	90	90	27	27	27	27	27	27	27	27

For the first series of the model evaluation we are forced to make the following simplifications:

- There are no plants inside the greenhouse.
- The optical characteristics of the glazing and the convection coefficients between the various surfaces are evaluated based on literature.

After the installation of sophisticated measuring equipment it will be possible to accurately validate the entire model.The results () show the typical rise in greenhouse temperature during the day, that reaches a maximum a couple of hours after midday. During sundown the greenhouse steadily loses heat but maintains a temperature 2-5 degrees higher than ambient during winter and 5-10 degrees during summer.

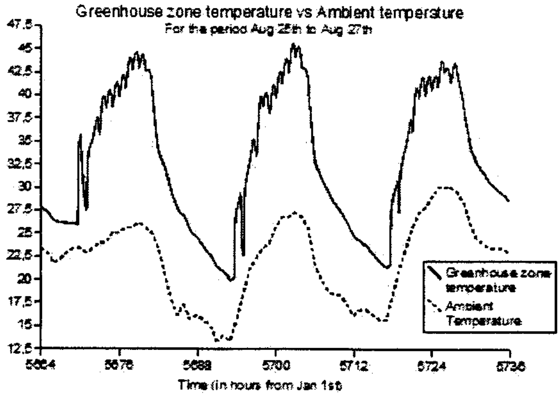

Figure 4. Greenhouse modelled temperature versus ambient temperature

The fuzzy controllers tested for their performance and corrected through studying of the simulations results. The fuzzy controllers were merged into the model as a separate macro model. All the set-points from the outer control loops were changed and the results were also bear in mind.

6. Conclusions

This greenhouse control seems to be quite efficient by achieving the desired factors that any cultivation demands. The testing of the controller through modeling shows that the set-points can be reached into the maximum possible values into the greenhouse. The system is still redesigned and improved through the consideration of the continuous measurements among the seasons. The most underlying characteristic is that this control is universal and can be used in any cultivation by setting the desired factors that a grower wants.

7. Acknowledgements

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8. References

[1]. Mavrogiannopoulos, Greenhouses, third edition,(in Greek) ISBN 960-351-378-4

[2]. Timothy J. Ross Fuzzy logic with engineering applications, McGraw-Hill 1995, ISBN 0-07-113637-1

[3]. D Driankov, H Hellendoorm,M. Reinfrank. An introduction to fuzzy control. Springer-Verlag 1993, ISBN 3-540-56362-8.

[4]. Joao M. C Sousa, Uzay Kaymak, Fuzzy Decision Making in Modeling and Control, World scientific, 2002, ISBN 981-02-4877-6

[5]. National strategy for the energy resources. Papadakis G, Gemptos Th,Georgakakis D, Giaglaras P, Derkas N, Karitsas K, Kittas K, Martzopoulos G, Nikita Martzopoulou, Souter Ch, Tsatsarelis K.2000

[6]. Thornley J.H.M, Hurd R.G. An analysis of the growth of young tomato plants in water

culture at different light intergrals and CO_2 concentrations. A mathematical model. Ann. Bot. 38, pp 389-400, 1974.

[7]. Stanhill G, The energy cost of protected cropping: A comparison of six systems of tomato production, J. Argic. Eng. Res. 25, pp.145-154, 1980.

[8]. Giaglaras P, Modelisation du fonctionnement de cultures ornementales sous serre, Application a l' evalution de strategies climatiques (enrichissement en CO_2 enclairage artificiel pour Begonia hiemalis.Ph.D. Thesis, University of Paris XI Orsay. 1996.

[9]. Abdullah Al- Faraj, Meyer G.E, Horst G.L, A crop water stress index for tall Fesque *(Festuca arundinacea Schreb.)* irrigation decision making-a fuzzy logic method.

[10]. Chou S.K, Chua K.J, Ho J.C, Ooi C.L. On the study of an energy-efficient greenhouse for heating cooling and dehumidification applications. Applied energy, 77, pp 355-373, 2004.

[11]. Lafont F, Balmat J-F. Optimized fuzzy control of a greenhouse. Fuzzy sets and systems, 128, pp 47-59, 2002.

[12]. O. Jolliet, HORTITRANS, a Model for Predicting and Optimizing Humidity and Transpiration in Greenhouses, Journal of Agricultural Engineering Research, 1994

[13]. G. Mavrogiannopoulos, Greenhouses: Environment, materials, construction, equipment (in greek), 2001

[14]. R.K. Sharma, G.N. Tiwari, Parametric study of a greenhouse by using Runge-Kutta methods, Journal of Energy Conversion & Management, 1999

[15]. M. Trigui, S. Barrington, L. Gauthier, A Strategy for Greenhouse Climate Control, Part I: Model Development, Journal of Agricultural Engineering Research, 2001

[16]. TRNSYS 15 Manual

[17]. R. K. Ursem, T. Krink, B. Filipic, A Numerical Simulator of a Crop-Producing

[18]. Greenhouse, EVALife Technical Report, 2002

Annex1:Nomenclature

A	Surface area
C	Heat capacity
CD	CO_2 mass flow rate
E	Water flux
E_{cl}	Water condensation on cladding
I	Radiation
I_{ps}	Photosynthetically active radiati
K_1	Infiltration constant
K_2	Infiltration constant
K_3	Infiltration constant
LAI	Leaf area index
R	Respiration rate
T	Temperature
T_r	Reference temperature
T_{sky}	Fictive sky temperature
U_{gl}	Glazing resistance to conductio
V	Volume
W	Crop CO_2 content
WS	Wind speed
c	CO_2 concentration
e	Humidity ratio
e_{sat}	vapor pressure at saturation
f	View factor
g_s	Leaf conductance to CO_2
h	Heat transfer coefficient
k_x	Constant x
$\dot{m}$	Mass flow rate
q	Heat flux
t	Time

α	Surface absorptivity to solar radiation
α_z	Zone air absorptivity to solar radiation
β	Fraction of beam energy received by a surface froma win
γ	Psychrometric constant
ϵ	Long-wave radiation emmisivity
θ	Angle of incidence
λ	Latent heat of vaporization
ρ	Surface reflectance to solar radiation
ρ_{air}	Zone air density
σ	Stefan-Boltzmann constant
τ	Surface transmissivity to solar radiation
ϕ	Photosynthesis efficiency

a	Ambient air
bm	Beam
df	Diffuze
em	Equipment
fl	Floor
fv	Forced ventilation
gl	Glazing
i	Glazing surface number
in	Infiltration
mc	Mechanical
o	Outside
pl	Plants
ps	Photosynthesis
rd	Radiation
rs	Respiration
tr	Transpiration
ug	Underground
z	Zone air