Modeling Passive Greenhouses. The Sun's Influence

M. M. Balas, V. E. Balas
"Aurel Vlaicu" University of Arad
77 Bulevardul Revolutiei
310025 Arad, Romania

***Abstract*–The paper is proposing a basic mathematical model of the solar effect in greenhouses, by means of the coefficient of the greenhouse effect that is linking the light intensity and the internal temperature of the greenhouse. The model is integrated into a structural deterministic model of a passive greenhouse.**

I. INTRODUCTION

The *Greenhouse Effect* is a very coined notion these days. Although its name, proposed by Jean Baptiste Joseph Fourier in 1824, is coming from the old gardening glass buildings, its meaning is linked to the overheating of the planets' surfaces due to atmospheres. Basically, the Sun is heating the Earth' surface by a wide range of visible and near infrared radiations, because the atmosphere is transparent to these radiations. On the other side, most part of the infrared radiations emitted by the Earth' surface is reflected back, because the atmosphere is opaque to infrared radiations. The term is considered by many as a misnomer, because it turned out that in the case of the gardening greenhouses, the major cause of the overheating is rather linked to convection, not to radiation, as experimentally proved by Robert Williams Wood in 1909. More precisely, the air inside greenhouses is warmed indirectly by the Sun, by means of the inside ground. The inside air is overheating because it is confined within the greenhouse, unlike the environment outside the greenhouse, where warm air near the surface rises and mixes with cooler air aloft. This can be demonstrated by opening a small window near the roof of a greenhouse: the temperature will drop considerably. The general concerning for the greenhouse effect is caused by the threatening global heating of the Earth.

Another term issued from the same old gardening item is *Glasshouse Effect*, nowadays used rather under its psychological connotations, referring to the consequences of the awareness of being under continuous surveillance.

This paper's is focused on the Sun's effect on gardening greenhouses, which will still be called Greenhouse Effect.

II. MODELING GREENHOUSES. THE STATE OF THE ART

The vast majority of the computer models labeled "greenhouse effect" is referring to the planetary feature. The issue is crucial for our future, but in the same time extremely complex, involving a huge amount of data, extensive computational resources and a deep understanding of the atmospheric phenomena and other related scientific disciplines.

Surprisingly, modeling the familiar gardening greenhouses is raising as well notable difficulties, caused by the complex physical interaction between the greenhouse constructive elements (walls, ground, heating, ventilation, etc.) and the environment (sun, wind, rain, etc.)

The computer models can be synthetic or structural. The synthetic models can solve the complexity of such systems, since they don't rely on real physical structures. Such models can be obtained using usual automate learning techniques, such as fuzzy reinforced learning [1], neural networks, genetic algorithms [2] or derived hybrid methods [3]. The above mentioned references are related to an experimental greenhouse, belonging to the Southern University of Toulon-Var, France, that may be accessed on Internet (*http://sis.univ-tln.fr /serre/*.) The constructive model belongs to Richel - Serres de France de Tarascon and the control equipment has an experimental character. The initiators of this project are Mr. Gilles Enéa and Mr. Jean Duplaix, of the team SIS/AI (*Signal, Information & Systems / Automatics & Images*).

Still, this approach has a short come: the synthetic models' validity domain is rather limited. In few words, synthetic models can be generated for specific weather conditions: sunny, cloudy, night, etc., but it's almost impossible to obtain a comprehensive model, that is working in all the possible cases. Moreover, the information about the systems' states is hidden, that is restricting the applicability of the synthetic models.

On the other hand, the structural models are capable to cover all the possible operational conditions; thanks to their transparency they can be used in a lot of engineering applications (self-adaptive control, CAD, automate diagnosis, etc.). Unfortunately their identification is very difficult because of the system's complexity.

A comprehensive image of the greenhouse system's physical structure is provided by R.J.C. van Oothegem in reference [4]. The thermal model alone is including eleven different convection effects (walls and roof – inside air, soil-inside air, ventilation, etc.) The model of the radiation is identifying twenty effects for long wave radiations and seven for short wave radiations. Besides the constructive parts of the greenhouse, an extensive model of the crop and its associate biophysical effects is also offered (evapotranspiration, respiration, photosynthesis, etc.) This work was performed as a project of the Dutch Governmental Research Program on Ecology, Economy and Technology. The aim of the project is to design a greenhouse without fossil fuel input. The model's main utility is to take part in optimal adaptive predictive control algorithms that minimize fossil energy consumption, tak-

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ing in account disturbances (weather forecast) and control inputs (valve positions, window aperture) [5].

Our team is collaborating with the Southern University of Toulon-Var in the computer modeling of the greenhouse. Our efforts are oriented to the structural modeling and some engineering applications [6], [7], [8], etc. The main physical effects within the greenhouse are identified with simple first order systems with nonlinear coefficients. A first manual identification is performed using particular weather conditions, in order to identify the parameters one by one, after the following itinerary: still night, windy night, sunny day, all with closed doors. The resulting sub models are then aggregated and used as a first guess in a final genetic algorithmic optimizing stage. Our experience is confirming that the first guess is essential for the convergence of the final optimization.

The most important engineering application is our variant of passive greenhouse [6], [9], [10].

II. THE PASSIVE GREENHOUSE

The *energetic passive greenhouse* or *passive greenhouses* are independent of the conventional energy sources (gases, liquid fuel or electricity). They are relaying on unconventional alternative energy sources like the sun light, the wind, the geo-thermal waters, etc. The passive solar greenhouses are already widely spread [11]. Their operation is consisting in the solar heating, the heat storage by diverse materials and the natural ventilation. An ideal passive greenhouse would use all the possible renewable energy resources, would be totally independent of any conventional energy sources and infrastructure and could be installed virtually anywhere on the surface of the earth.

The main advantages of the passive solar greenhouses are:

- the low costs of the operation: in fact the energy cost is simply disappearing;
- the independence of the conventional energy infrastructures (hot water, gas or electricity).

The basic limitation of these greenhouses is bounded by the climate and weather. Under a certain mean temperature the sun alone can not ensure the heat losses, and the unconventional energy sources are not very constant and reliable. For instance the climatic conditions are heavily influencing the solar and the wind energy. That is why several complementary energy sources must be aggregated, in order to cover any possible operating conditions.

Our first passive greenhouse version is provided by a cold water heat pump and a wind turbine.

The heat pumps [12], [13], [4] can extract energy from low temperatures waters or even air and to inject it into closed water pipes heating installations. There are two constructive options: either with two water wells or with an underground pipes web. The water extracted from the first well is introduced into the pump, where it leaves a part of its thermal energy, loosing several degrees of its temperature. After that the water is exhausted into the second well. Between the two wells an underground water circuit is created. A similar insulated circuit may be realized by underground pipes. During the underground circulation the water is re-warmed by the energy provided by the thermal radiation of the earth. The heat pump is reversible, during hot weather they can operate as coolers.

Obviously this type of energy is available virtually anywhere under the surface of the earth, it is not influenced by weather, is free of any costs and it has no predictable time limits. They still need a small external energy amount, with the purpose to re-circulate the water. The energy balance is very favorable: for a heating power of 5-6W only 1W has to be spent for the recirculation.

That's why we proposed to use a second alternative energy suplyier: a wind generator. The wind has only to provide the recirculation energy needed by the heat pump, so the dimensions and the price of the wind generator system are not excesive. A second positive contribution of the wind generator was analysed in [8]: the compensation of the suplementary heat losses caused by the wind itself to greenhouses.

Eventually we decided to introduce a third energy source: the solar panels, as shown in fig. 1.

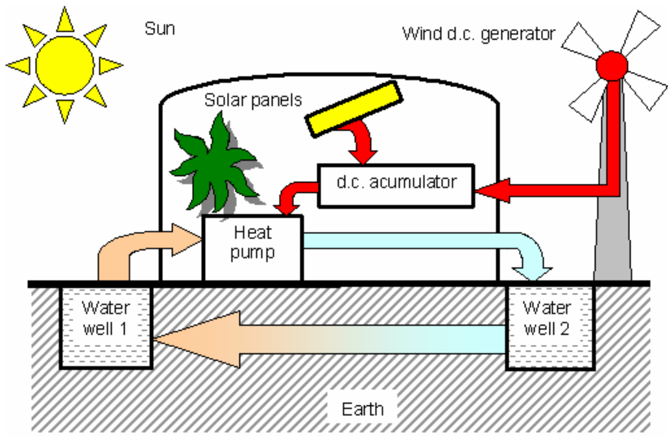

Fig. 1. The heat pump / wind turbine / solar panel greenhouse

At the first sight this element could seem redundant, and even unadvisable, since the sun is anyway heating the greenhouse. However, as one can observe in all the modern greenhouses, when the solar radiation is very high greenhouses would overheat, hence the necessity of a particular constructive element: the curtain (screen). When deployed, the rolling curtain is protecting the plants against over heating and over illuminating during sunny days, and is preserving a layer of warm air near the ground during cold nights. A matrix composed by orientable amorph silicon photovoltaic panels would produce electrical energy and shadow the plants in the same time. The supplementary solar energy will supply the electronic circuitry necessary for the automate control and for communications as well as the electric driving systems that are needed for feeding and watering the plants.

We are studying the above described structure by computer simulations as well as by experimental tests performed on a reduced scale model.

IV. THE SOLAR EFFECT FIRST GUESS MODEL

The fundamental effects in greenhouses, besides any other energy source, are those produced by the sun. Surprisingly, we did not find, at least for the time being, a suitable computer model of the sun's effect over a greenhouse. That is why we are now proposing a "first guess" computer model for the cumulated radiation + convection effects of the sun, that is simply linking the solar illumination measured in W/m^2 with the active power that is effectively heating the inside air. The Matlab-Simulink implementation of the model are presented in the following figures.

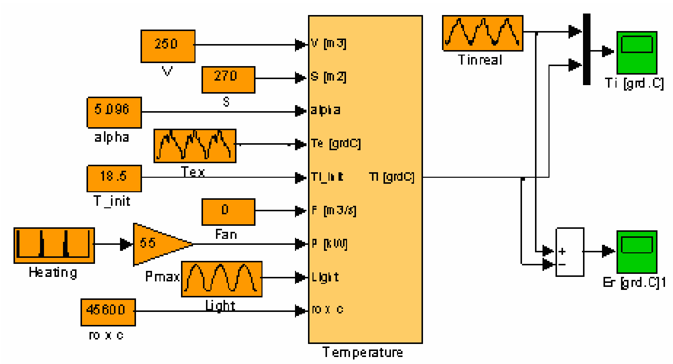

Fig. 2. The main window of the model

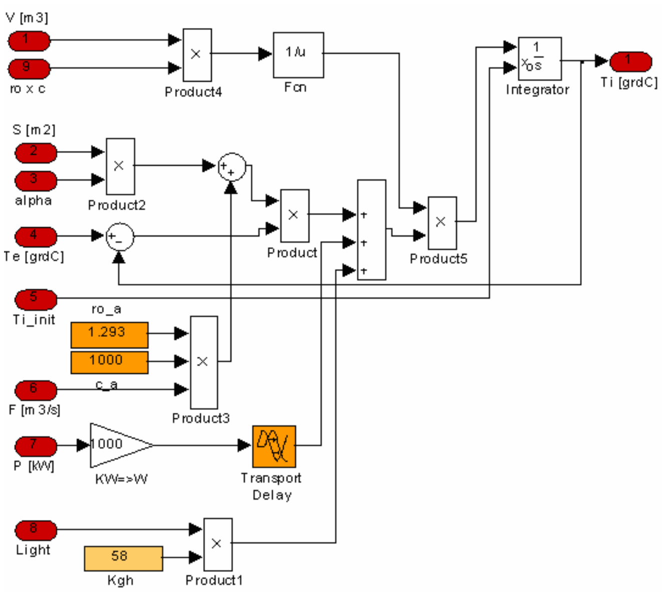

Fig. 3. The model of the differential equation

The model is represented by the following equation [7]

$$V \cdot \rho_g \cdot c_g \cdot \frac{dT_i(t)}{d(t)} = \alpha \cdot S_w \cdot [T_e(t) - T_i(t)] + G(t) + P(t-\tau) \qquad (1)$$

where $\alpha = 5.096$ $W/m^2 \cdot K$, $\rho_g \cdot c_g = 4560 J/kg \cdot m^3$ and $\tau = 150s$ [8]. The influence of the wind is neglected, by choosing a still sunny day's data (see fig. 4). We are interested in modeling the heat flow produced by the solar illumination G [W].

TABLE I
THE VARIABLES OF THE MODEL

Entries	Meas. unit	Type	Meaning
V	m^3	input	the internal volume of the greenhouse
S	m^3	input	the total surface of the walls of the greenhouse
α	$W/m^2 \cdot K$	input	the mean heat transmission coeff. through the walls
Te	^0C	input	the outside air temperature
Ti_init	^0C	input	the initial inside air temperature
Fan	m^3/s	input	the fresh air flow
P	kW	input	the power of the heating device (0/1)
Light	W/m^2	input	the solar illumination
roxc		input	the the product of the equiv.alent density and specific heat of the inside of the greenhous
Ti	^0C	output	the inside air temperature

As explained before, the model is as simple as possible:

$$G(t) = k_{gh} \cdot L_{ight}(t) \qquad (2)$$

where k_{gh} is *the coefficient of the greenhouse effect*, measured in squared meters. This coefficient can be as well measured in W/lx if the illumination is measured in lx. We are considering a constant k_{gh} for the moment, but in the next stage of this study, a functional dependence k_{gh}(Fan) is to be established.

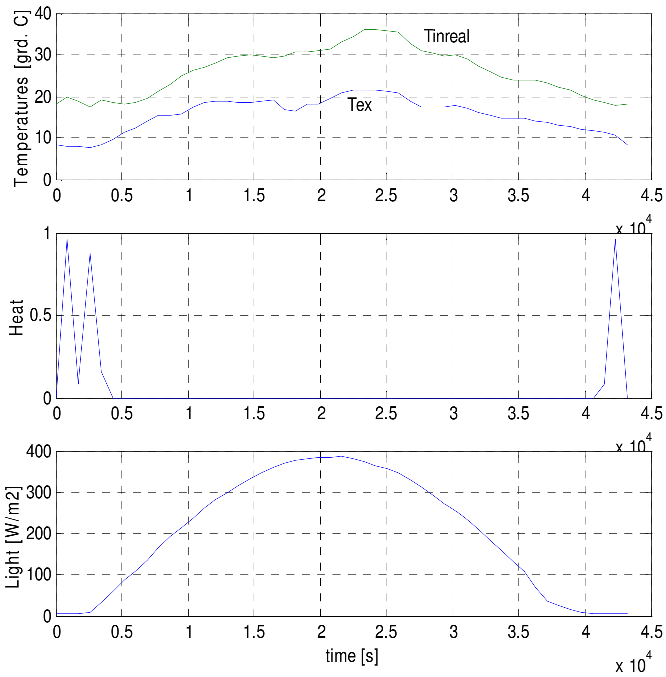

Fig. 4. The recorded data of the Toulon greenhouse for a sunny day (09.Feb.2004)

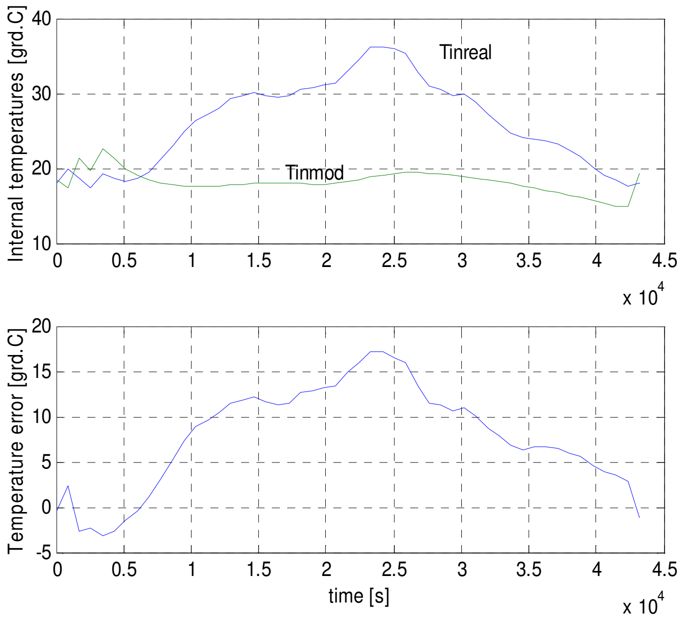

Fig. 5. The results of the simulation with $k_{gh} = 0$

V. SIMULATION RESULTS

The simulations are lasting 12 hours, from 7:00 a.m. to 19:00. The results of the simulation with $k_{gh} = 0$ are presented in fig. 5. As one can observe, the temperature error between the model and the real greenhouse $\varepsilon = T_{inreal} - T_{inmod}$ is reaching 17.5^0C.

The manual identification of k_{gh} is presented in fig. 6. The value that is producing the best overall similarity between Tinreal and Tinmod, was $k_{gh} = 58$. In this case abs(ε) < 6°C.

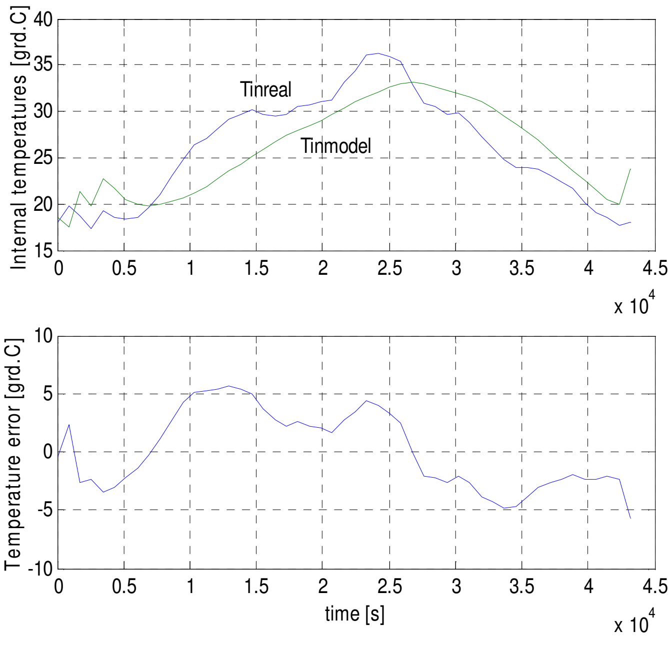

Fig. 6. The results of the simulation with $k_{gh} = 56$

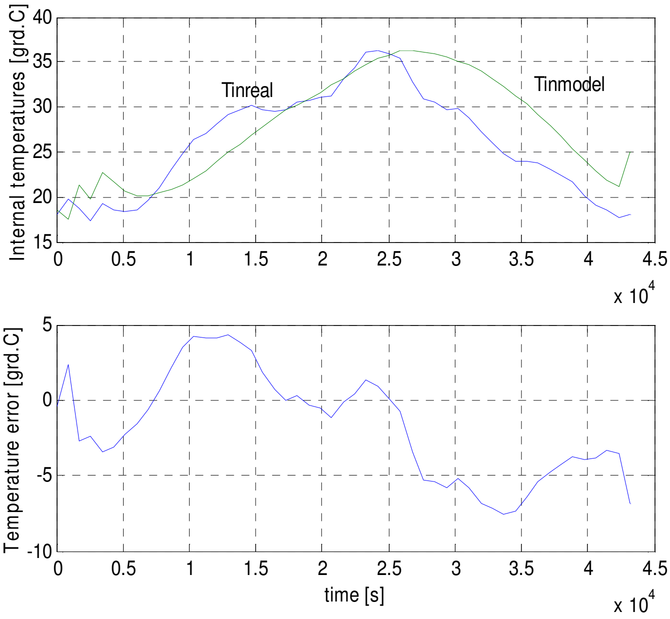

Fig. 7. The results of the simulation with $k_{gh} = 72$

The previous simulation produced a lower maximum value for Tinmod.

Another simulation is performed with the purpose to find the k_{gh} value that is producing the same maxima for T_{inreal} and T_{inmod}. The simulation is presented in fig. 7. The new resulted value is $k_{gh} = 72$.

Because the errors for the second half of the day are too high, we are not recording this value, remaining for the time being at $k_{gh} = 58$. The result of the identification is:

$$250 \cdot 4560 \cdot \frac{dT_i(t)}{d(t)} = \tag{3}$$

$$= 270 \cdot 5.096 \cdot [T_e(t) - T_i(t)] + 58 \cdot L_{ight}(t) + P(t\text{-}150)$$

or

$$1.14 \cdot 10^6 \cdot \frac{dT_i(t)}{d(t)} = \tag{3a}$$

$$= 1.37592 \cdot 10^3 \cdot [T_e(t) - T_i(t)] + 58 \cdot L_{ight}(t) + P(t\text{-}150)$$

The discrete time version is :

$$1.14 \cdot 10^6 \cdot [T_i(t+1) - T_i(t)] = \tag{3b}$$

$$1.37592 \cdot 10^3 \cdot [T_e(t) - T_i(t)] + 58 \cdot L_{ight}(t) + P(t\text{-}150)$$

The simulations are producing o rough approximation of the solar illumination effect and it seems that the ±6°C error can not be reduce any further by the present simplified model (3). The persistence of positive errors in morning and negative errors in evening is repeatable and it must be correlated to the other state variables of the systems. Two important parameters that have the potential to significantly influence the systems are not disposable: the ground temperature and the position of the access door.

An intriguing fact is the delay of the model (3) compared to the real greenhouse. We have not yet a valid explanation for this fact.

Besides its limitation, the "first guess model" of the solar effect in greenhouses can already help us in building an aggregate model of the passive greenhouse. As we observed in ref. [9], a greater number of parameters is not necessarily threatening the genetic algorithms' convergence, so the aggregate model should help us to refresh our image on model (3).

VI. AN INITIAL GUESS MODEL FOR THE PASSIVE GREENHOUSE

The main designing problem of the fig. 1 energetic passive greenhouse is the correct dimensioning of the energy sources. Heat pumps, wind turbines and solar panels have by now created their own well established markets, with several producers and a wide offer of constructive models and technical data [12], [14], [15]. Our goal is to build a computer model of such a greenhouse, able to assist when choosing and sizing the energy sources, in an optimal manner.

The solar illumination and the wind, together with the heat pump will replace the heating equipment in equation (1), for the thermal model:

$$V \cdot \rho_g \cdot c_g \cdot \frac{dT_i(t)}{d(t)} = \quad (4)$$

$$\alpha \cdot [1 + k_w \cdot V_w(t)] \cdot S_w \cdot [T_e(t) - T_i(t)] + k_{gh} \cdot L_{ight}(t) + P_{hp}(t)$$

where V_W is the wind's velocity, P_{hp} is the power provided by the heat pump and the coefficients k are modeling the influence of the main physical factors on the system: k_w for the energy looses caused by wind, k_{gh} for light, k_{wm} for the wind generator.

The accumulator's feeding power P_{dc} that is either stocked or used for the recirculation of the heat pump and for the supplying of the control equipment, is:

$$P_{dc}(t) = k_{wm} \cdot V_w(t) + k_{sp} \cdot L_{ight}(t) \quad (5)$$

where k_{wm} is the coefficient of the wind turbine and k_{sp} is the coefficient of the solar panels.

VII. CONCLUSIONS

The paper is proposing a "first guess" model of the solar effect on greenhouses. The model is meant to be used for the dimensioning of an original energy passive greenhouse, provided by a cold water heat pump, a wind generator and solar panels.

The sun's effect is modeled by a coefficient of the greenhouse effect that is directly linking the solar illumination with the internal temperature.

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