A VALIDATED PHYSICAL MODEL OF GREENHOUSE CLIMATE

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Abstract

In the greenhouse model the momentaneous environmental crop growth factors are calculated as output, together with the physical behaviour of the crop. The boundary conditions for this model are the outside weather conditions; other inputs are the physical characteristics of the crop, of the greenhouse and of the control system. The greenhouse model is based on the energy, water vapour and CO_2 balances of the crop-greenhouse system. While the emphasis is on the dynamic behaviour of the greenhouse for implementation in continuous optimization, the state variables temperature, water vapour pressure and carbon-dioxide concentration in the relevant greenhouse parts crop, air, soil and cover are calculated from the balances over these parts. To do this in a proper way, the physical exchange processes between the system parts have to be quantified first. Therefore the greenhouse model is constructed from submodels describing these processes:

a. Radiation transmission model for the modification of the outside to the inside global radiation.
b. Ventilation model to describe the ventilation exchange between greenhouse and outside air.
c. The description of the exchange of energy and mass between the crop and the greenhouse air.
d. Calculation of the thermal radiation exchange between the various greenhouse parts.
e. Quantification of the convective exchange processes between the greenhouse air and respectively the cover, the heating pipes and the soil surface and between the cover and the outside air.
f. Determination of the heat conduction in the soil.

The various submodels are validated first and then the complete greenhouse model is verified.

1. Introduction

In a relatively short period greenhouse operation has evolved from an experience based to a science based activity. Driving forces for this evolution were the strong needs to control or even reduce the costs of operation in spite of rising supply costs (like energy), and to raise the level of both quantity and quality of greenhouse production. The evolution became possible by the development of various scientific tools and the improvement of available technical equipment. While a greenhouse is a complex production system, in which physiological and physical processes cooperate and have to be controlled keeping in mind horticultural constraints, a systems approach is suited to combine the insights from the various supporting disciplines (Udink ten Cate et al., 1978). This was the starting point for the development of a dynamic physical model of greenhouse climate (Bot, 1983). This model had to describe the greenhouse climate in a dynamic way on a minute base to support the development of control strategies to optimal control and to serve as a tool in the analysis and design of greenhouses in dynamic conditions, as meteorological conditions in north-western Europe are. The model had to calculate the momentaneous crop growth conditions (greenhouse climate on a minute base) as output which can serve as an input for dynamic crop growth models (Challa et al., 1988). Moreover the momentaneous energy consumption together with the carbondioxide and water losses from the greenhouse are calculated as outputs, serving as input for optimization strategies Van Henten, 1988). The boundary conditions of the model are the dynamic outside weather conditions, other inputs are the physical characteristics of the greenhouse, of the crop and of the control system.

While the various physical processes in the greenhouse drive the greenhouse climate it is an impetus to describe these processes first in a sound way before combining them to a total description of the greenhouse climate. Therefore the total model was composed from the description of the various physical processes as submodels. These submodels were validated first in-situ and then combined to a total model which then had to be tuned on minor aspects only.

2. Submodels

As the model has to describe the spatial average greenhouse climate on a minute base, the energy buffering in the components greenhouse air, crop, cover and soil has to be taken into acount (Bot, 1988). Therefore the greenhouse system is composed from these components (fig. 1) and the energy and mass (water vapour and carbondioxide) balances are set up over these parts to calculate the respective temperatures and concentrations. In principle the set-up of the model is therefore the same as pointed out already in the first model study on greenhouse climate (Seginer and Levav, 1971) and succeeding studies as overviewed earlier (Bot, 1983). The recent model differs in the seperate validation of the various transfer processes in the greenhouse. In the balances the in-and outflux of energy and mass for each component have to be quantified in an accurate way. The submodels for short-and longwave radiation, ventilation, crop behaviour and convective and conductive transfer define these fluxes (fig. 2) so are the base for the total model.

2.1. Transmission of shortwave radiation

The radiation transmission model modifies the outside to the inside global radiation. The greenhouse transmission is calculated from the radiation conditions (i.e. the composition of the global radiation in direct and diffuse radiation) and the transmission for direct and diffuse radiation. These transmissions are calculated from the optical properties, sizes of the constructive parts, geometry and orientation and position of the greenhouse and from the solar position and the characteristics of the diffuse radiation, applying optical and goniometric laws (Bot, 1983). This submodel was checked under various radiation conditions for Venlo type greenhouses with and without thermal screens. Under complete diffuse radiation (high cloudiness, low solar altitude) the measurement of transmission is relatively simple due to the constant conditions. The spatial average of the measurements was compared to the model calculations and proved to be in agreement within a few percents of transmission. For radiation conditions with a high amount of direct radiation (low cloudiness) the measurement of momentaneous transmission is very difficult due to the shaded areas under the greenhouse cover. Therefore the model was checked on measurements of the daily sum of global radiation inside and outside the greenhouse to integrate local effects in time. Also for this kind of radiation cvonditions the measurements and calculations were in agreement within a few percents of transmission.

The submodel of radiation transmission is operational to determine the momentaneous radiative energy input to the various greenhouse parts in the greenhouse climate model and to calculate the radiation regime above the crop as input for a crop growth model (Gijzen and ten Cate, 1988, Houter, 1988).

2.2. Air exchange by ventilation

The ventilation model describes the ventilation exchange between the greenhouse interior and the outside air. The volume flux of exchanged air is calculated from the driving forces for air flow (wind characteristics and/or temperature difference between the interior and the exterior) and from the flow resistance of the ventilation openings (determined by the geometry and opening angle of the ventilators). The first version of this submodel (Bot, 1983) is applied in the reported greenhouse climate model and in CO_2 optimization studies (Houter, 1988). Recent efforts are aimed at generalizing this submodel for various window types, various greenhouse geometries and sizes and at checking of assumptions made in the first version (De Jong, 1988).

2.3. Physical characteristic of the crop

The exchange of energy and mass between the crop and the greenhouse environment is calculated in this submodel. First of all the physical properties of the crop have to be described, as defined by the internal and external crop resistance. The internal crop resistance is found to be dependent on the radiation intensity at crop level, on the temperature, on the water vapour deficit and on the CO_2 concentration and is validated (Stanghellini, 1987). The definition of physical crop properties deserved special attention.

2.4. Energy and mass transfer

2.4.1 Thermal radiation exchange

The thermal radiation exchange between the various greenhouse parts is calculated according to the well known Stefan-Boltzmann equations, including view-factors. The accurate determination of the view factors between the crop and its environment vary with the development of the crop (Stanghellini, 1987). From measurements of the net radiation the calculations proved to be realistic.

2.4.2. Convective exchange processes

This submodel calculates in seperate modules the convective exchange of energy and mass between the greenhouse air and respectively the cover, the heating pipes and the soil surface and between the cover and the outside air. In general these processes are not properly quantified in general heat transfer literature and therefore are quantified in-situ (Bot, 1983, 1988). From general literature it is known that the convective energy transfer can be described in terms of the dimensionless numbers of Nusselt (Nu), Reynolds (Re) for forced convection, Grashof (Gr) for natural convection and Prandtl (Pr). This allows the comparison of literature data and measurements.

Though it was expected that the exchange between the cover and the outside air is due to forced convection, it proved to be in the transition region between natural and forced convection for wind speeds below 3-4m/s. The exchange from the greenhouse air to the soil surface and to the cover is due to natural convection, that between the air and the heating pipes or the leaves have a forced convective component too, due to the small characteristic lengths of pipes and leaves.

2.4.3.Heat conduction in the soil.

The energy storage in the soil is an impetus for the accurate calculation of the dynamics of the greenhouse climate for various time scales (Bot, 1988). Moreover the momentaneous soil surface temperature has to be determined while it interferes with the momentaneous temperatures of the crop, the greenhouse air and the cover. To meet these requirements the soil is divided in 7 layers with increasing thickness; a thin layer of 1cm at the surface and deeper layers with double thickness of the preceeding layer. The thermal conductivity of the soil is measured in-situ with a special probe, applying an accurate, nonsteady-state probe technique (Van Loon et al., 1988). The soil heatflux was measured by flat plate flux sensors.

3. Total model

After validation of the submodels the total greenhouse climate model was checked by comparing the calculations with experimental data of the climate on a minute base in greenhouses with and without thermal screens (Van het Ooster, 1983, De Jong, 1984) and with single and double glazing (Van Strien, 1987, Bot et al., 1988) under various meteorological conditions. In figs. 3 and 4 measurements and calculations of greenhouse air temperature and leaf temperature are compared during a period with varying meteorological conditions. In this period a day with heavy varying cloudiness is followed by a night in which the cloudiness decreases and then is followed by a clear day. There is a good agreement between the measurements and the calculations for the variations both on a small and on a large time scale. In the original model pipe temperature and ventilator settings are boundary conditions, so the model can be checked with a data file containing pipe temperature and ventilator setting. For new conditions pipe temperature and window setting are state variables too, calculated from set-points for air temperature and humidity using some control algorithm for the mixing valve and ventilator setting. This was implemented in the model, allowing the choise of set-points and control algorithms for mixing valve and ventilator setting. In fig. 5 a simple day-night air temperature set-point cycle is showed together with the calculated response of the greenhouse system. Output (energy consumption) of the model with mixing valve control and of versions adapted to other glazings (e.g. hortiplus) was also compared to results of a model which was validated by extensive measurements under different conditions (Jolliet, 1988) and proved to be in accordance with that model for energy consumption. This supports the opinion that a physical model can be adapted to other conditions and greenhouse characteristics in a relatively easy way.

4. Conclusions

A dynamic physical model, composed of seperately validated submodels is a reliable tool for optimization studies, greenhouse analysis and design. The model can be used under conditions that are different from that under which the model is validated.

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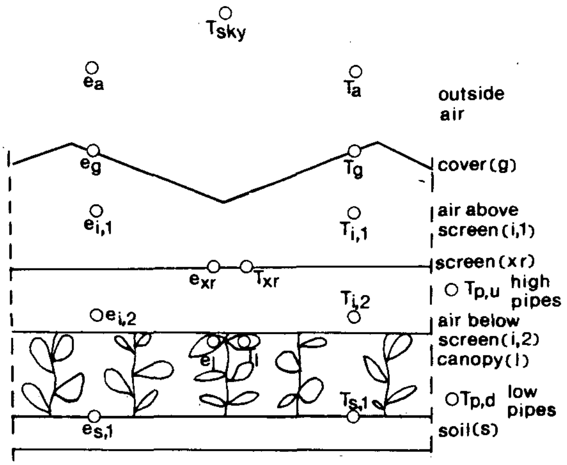

Figure 1. Compartimentation of the greenhouse model.

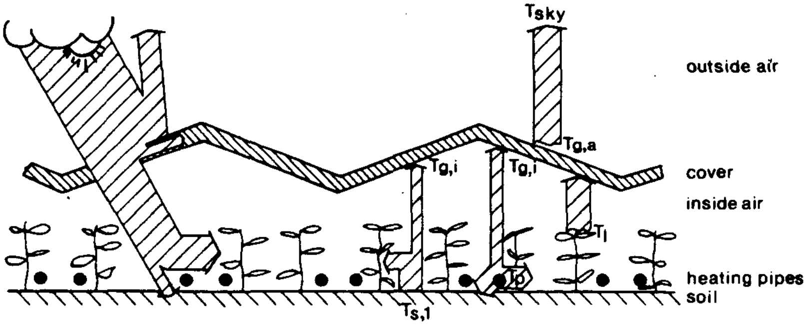

Figure 2.a. Interaction of shortwave radiation and longwave radiation exchange.

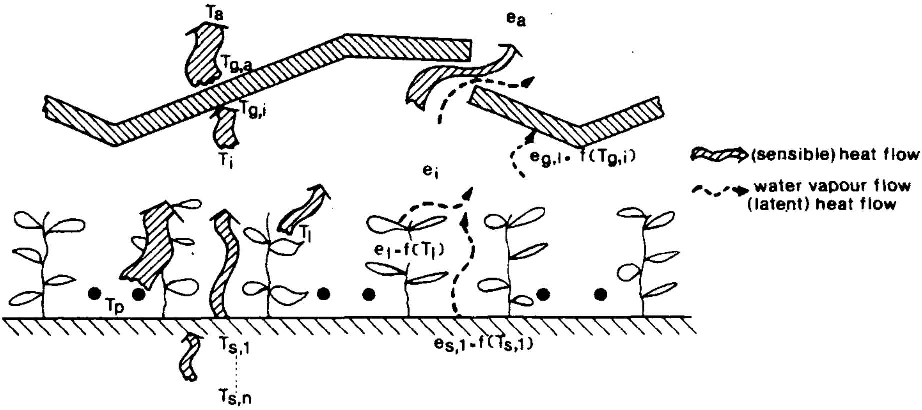

Figure 2.b. Energy and mass exchange between the various greenhouse compartments.

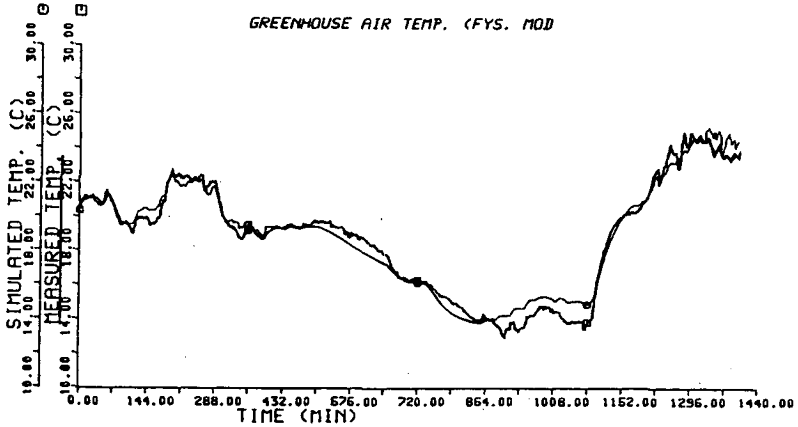

Figure 3. Comparison of measured and simulated air temperatures during a 24-hour period.

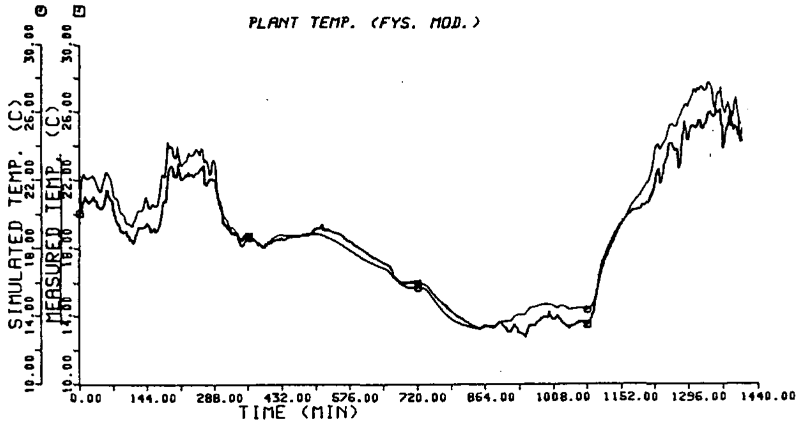

Figure 4. Comparison of measured and simulated plant temperature during the same period (fig. 3).

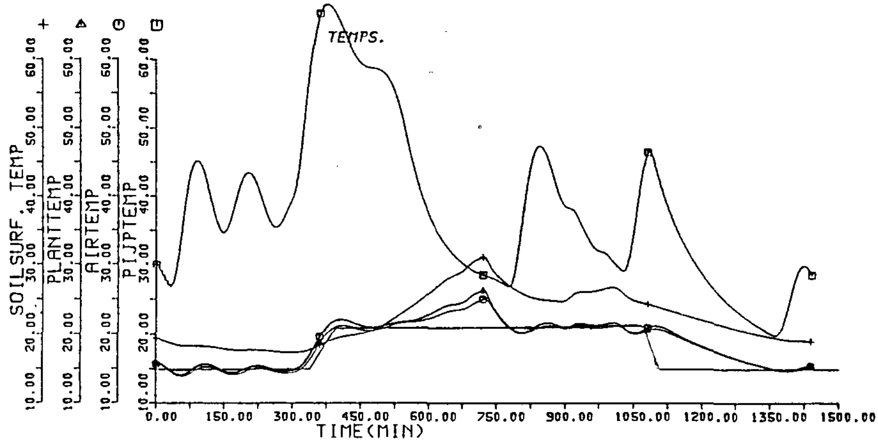

figure 5. Simulated temperatures of heating pipes, air, crop, soil surface during a 24 hour period.