DYNAMIC MODELLING OF GREENHOUSE CLIMATE USING A MINICOMPUTER

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Abstract

A systems approach to greenhouse climate research is outlined. A model, based on the heat and water vapour balances in a compartimented greenhouse is described. The model is presented in bond graph notation to have a clear insight in the physical structure of the model and to simulate it in an easy way on a minicomputer. The application of models in a hierarchical control system configuration is discussed.

1. Introduction

In the search for energy savings in protected cultivation, a large amount of direct methods are under study presently, or are applied already. This direct methods vary from complete new greenhouse structures to the application of thermal screens. In general these methods approach the problem from a technical point of view.

A different approach - often called the systems approach is to consider plant production and its associated energy cost a production system that should be controlled to yield an "optimal" performance. Roughly stated three hierarchical levels of control can be distinguished.

I) The control of heating and ventilation to ensure a desired glasshouse climate, independent of the disturbances caused by the weather. Good control on this level will result in energy savings due to the prevention of overheating and of simultaneous heating and ventilation. The usually applied automatic analogue controllers do work on this level.

II) The control of short term conditions to ensure optimal plant growth. Whereas the glasshouse climate itself is controlled on the previous level, the desired values of the climate factors are determined and controlled on this level. The airtemperature, for instance, is often automatically increased in accordance with the radiation intensity. Condensation on leaves and flowers should be avoided to prevent diseases and damage. The underlying ideas on this level are partly physiological and partly empirical.

III) The ultimate control level is that of the long term plant development. The short term plant situation should be related to plant development and production. Some empirical rules and much of the growers experience is decisive here. This field is a main challenge for horticulturists.

A basic tool of the systems approach is the mathematical model. In the discussed subject models of the micro-climate will be needed on all levels, models of plant growth are needed on level two and three and of plant development on the third level. The ultimate object being improved control, one approach is to incorporate models in a learning control strategy. This implies that the models can be more simple than the conceptual or explanatory models usually applied in research. If the model contains a few unknown parameters an on-line parameter estimation technique can be used for updating. As is shown by Udink ten Cate et al. (1977) even a simple black box model, not containing physical but only input-output relations, can give a significant improvement over conventional control.

2. Glasshouse climate

Glasshouses are built to improve the environmental factors for plant production. The factors of interest are radiation, temperature, relative humidity, carbon dioxide concentration and wind velocity. First of all these factors are influenced by the reduction of the turbulent exchange. This effect mainly effects the temperature rise in the glasshouse (Lee, 1973).

Another effect is the so called "greenhouse effect": the glass is transparant for the solar short wave radiation but not for the thermal radiation emitted by the soil and plants. This effect causes ten to twenty percent of the temperature rise.

Compared with other buildings a glasshouse is an open system in which the climate is influenced directly by the outdoor climate. But compared with the climate in the open, the glasshouse climate is that of a closed system in which the heat and vapour exchange inside directly influences the climate. So both a translation from outdoor to indoor climate and a description of plant behaviour is needed to determine the environmental factors near the plant. These factors in turn determine plant behaviour so only a description of the total system will be succesful.

To understand the heat and mass transfer between plants and atmosphere a short description of this aspect of plant behaviour is essential. The main plant processes involved here are photosynthesis and transpiration.

Photosynthesis is determined as main factor by short wave radiation, carbondioxide concentration and temperature. Only a small, almost negligible amount of the short wave radiation is directly absorbed in the photsynthesis proces. The main part is absorbed by the leaf, leading to a temperature rise of the leaf. To prevent a too large temperature rise it is cooled by transpiration, the water being transported from the roots to the inner parts of the leaf and then evaporated to the atmosphere.

For the absorption of carbondioxide and the evaporation of water vapour, the leaf has small holes or stomata in the surface. For photosynthesis these holes have to be wide to support carbondioxide. In this situation, however, water is evaporating producing a possible water shortage in the leaf. To control these phenomena the aperture of the stomata is regulated by internal plant processes, dependent on photosynthesis, transpiration and water content of the leaf (Raschke, 1975; Takakura et al., 1975) which in turn are dependent on the local environmental factors.

3. Climate model

In the climate model the heat and water vapour flows are considered in a compartimented glasshouse.
The compartments in the model are the glass-cover, the inside air, the plants (or canopy), and some layers in the soil.
This is only a rough compartimentation, but measurements justify this approach for a model which only includes total heat and mass exchange of the canopy.

The main incoming energy flow is short wave solar radiation. Sometimes a glasshouse is regarded as a large radiation collector, converting solar energy into plant production. The incoming solar energy is partly absorbed, reflected and transmitted by the glass-roof and walls. The transmitted radiation is again partly absorbed, reflected and transmitted by the canopy and then by the soil. From the known optical properties of the cover, the canopy and the soil, the total absorbed amount of incoming solar energy is determined. In the model the optical properties were assumed to be constant, though the reflection, which is dependent on the direction of the incoming radiation is changing during a day and during a year. For the glasshouse under consideration the absorbed percentages were 40% for the cover, 27% for the canopy and 16% for the soil, 12% was reflected directly by the cover and the remaining 5% was reflected by the canopy and the soil and transmitted to the atmosphere.

The incoming thermal or terrestrial radiation is described in literature by empirical formulas because of the complexity of the mechanism. Wartena et al. (1973) reviewed various methods and compared them with measurement data. The results turned out to be so inaccurate that it is not justified to include terrestial radiation in the model. Under certain meteorological conditions however, e.g. in clear nights without wind, or even on clear days, this will be a shortcoming.

On the contrary, thermal radiation exchange in the glasshouse between cover, canopy and soil is of interest. Because of the relatively small temperature differences, the Stephan Boltzmann formula is linearised. As stated in the discussion on the "greenhouse effect" the reduction of the turbulent exchange is of main importance. The related transport process is ventilation, transporting both heat and water vapour to and from the air compartment.
The incoming heat flow by ventilation $\psi_{h,vent.\ in}$ is given by:

$$\psi_{h,vent.\ in} = \psi_v\ \rho\ C_p\ T_{out} \qquad (2)$$

The incoming water vapour flow $\psi_{w,vent.\ in}$ is also determined by ψ_v according to:

$$\psi_{w,vent.\ in} = \psi_v\ (m\ /\ R\ T_{out})\ e_{out} \qquad (3)$$

The same formulas with of course T_{in} and e_{in} instead of T_{out} and e_{out} are valid for the outflowing heat and water vapour flow.
The amount of exchanged air ψ_v is dependent on the position of the window, the outside wind velocity and direction, and to a lesser degree on the temperature difference between in- and outside air.
Satisfying relations are not reported in literature. We started model experiments in a windtunnel to find the relation between air exchange, window position and wind velocity. Full scale experiments should validate the results.
In the present model ψ_v is based on forced ventilation data or estimations in a natural ventilated glasshouse.

In the model the mechanism of convection is treated in the usual way by using dimensionless relations. For the convective exchange between cover and outside turbulent airflow, the heat transfer coefficient is assumed to be:

$$Nu = 0{,}03\ Re^{0{,}8} \qquad (4.a)$$

resulting in $\alpha = 5,5 \ v^{0,8} \ l^{-0,2}$ (4.b)

with air properties at about $10^{o}C$. Determining a more accurate relation is not so interesting, since the largest convective resistance exists between cover and inside air. Inside the glasshouse a combination of circulation and free convection is present along the glass, due to the temperature difference between glass and inside air. The natural convective heat transfer coefficient between a vertical wall and inside air is for the turbulent region given by:

$$Nu = 0,1 \ Gr^{1/3} \ Pr^{1/3} \quad (5.a)$$

resulting in:

$$\alpha = 0,125 \ (\Delta T)^{1/3} \quad (5.b)$$

The forced convective heat transfer is still given by (4).
For the low inside air velocity of about 0,1 - 0,25m/s the forced and free convective heat transfer have about the same magnitude. The result is a heat transfer coefficient of about 5 W/m^2K. For the almost horizontal roof (an angle of 26^{o} between roof and horizon is applied for a common type of glasshouse), the natural convection will be somewhat smaller, the total result however will be similar. So the inside heat transfer coefficient is fixed to a value of 5 W/m^2K. More accurate figures can be expected when the inside circulation as a function of ventilation and natural convection along the heating pipes is determined. In the present research programme on ventilation this subject is pursued. For the convective heat transfer between inside air and soil, natural convection will be the most important mechanism; the circulation is decreased in the canopy. Therefore, a heat transfer coefficient of 3,5 W/m^2K is selected. Along the leaves forced convection will dominate.
A great variety of relations is found in literature (Stigter, 1972):

$$\alpha \doteq (4 \text{ à } 13) \ v^{0,5} \ l^{-0,5} \quad (6)$$

This might be motivated because the relations with the low coefficient have to be applied on both sides of the leaf but in the relations with the high coefficients both sides of the leaf are already incorporated. This is however not always stated clearly. As a compromise $\alpha = 5 \ (v/l)^{0,5}$ is used, applied on both sides of the leaf. With low windspeed of about 0,1 m/s and a leaf width of 5 cm, α will be 7 W/m^2K.

The convective mass transfer coefficient k is related to the heat transfer coefficient α according to

$$k \simeq \alpha / \rho \ C_p \quad (7)$$

So in the water vapour model the convective mass transport is determined from the convective heat transport in the temperature model. For the plant compartment we have taken into account the stomatal resistance according to section 2.

In the soil, heat transfer by conduction is considered between the soil compartments. Due to the assumed constant water content of the soil (in glasshouses the soil is kept moisty) the heat conductivity is assumed constant at 2 W/mK.

4. Bond Graph representation and interactive simulation

The relatively novel bond graph notation (Karnopp et al., 1972; Oster et al., 1973) is chosen for the representation of the model for the following reasons:

- it represents the physical structure in an easily recognisable, compact way
- computational problems can be detected and remedied in the bond-graph
- it is readily converted in a simulation programme, suited for interactive simulation by using the block oriented simulation language THTSIM (Kraan, 1974)

Moreover it can also easy be translated into a set of differential equations, that can be solved by programming in CSMP.

Fig. 1 shows the bond graph of the simplified glasshouse model. The nodes or "0-junctions" represent the distinct temperatures or vapour pressures in the model. The line elements or "power bonds" correspond with energy flow, the half arrow indicating the prescribed positive direction. A bond is actually a shorthand notation for the interaction between components and involves two signals.

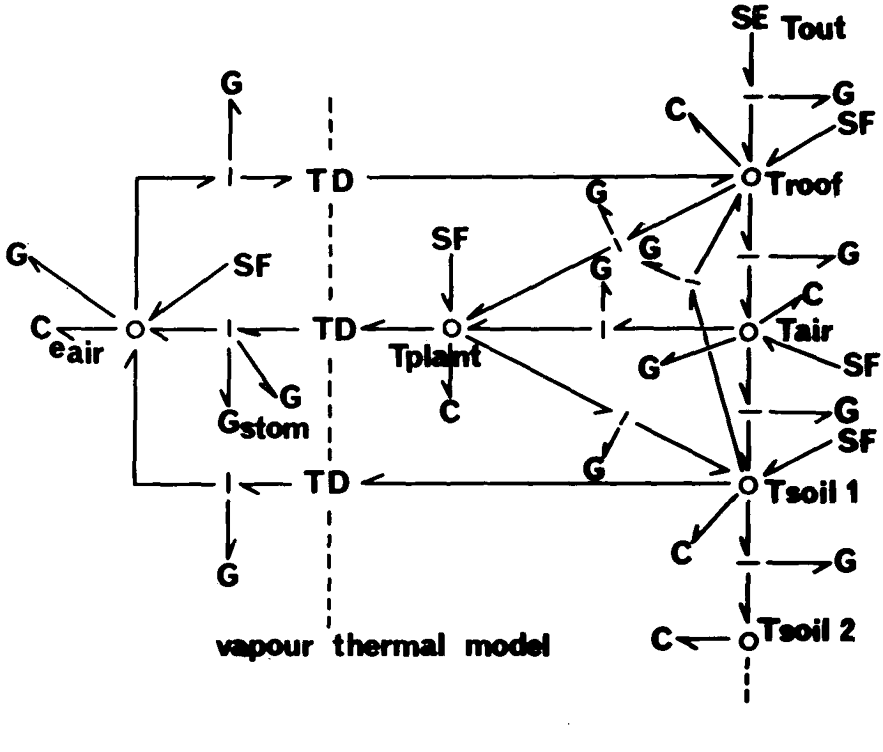

fig. 1. Bond graph of simplified glasshouse

On the top of the right side or thermal part of the model the direct and diffuse radiation is represented by a time dependent source of heat flow (SF), acting on the heat capacity (C) of the roof. From this "T roof" the heat flows in several directions via "1-junctions" to which heat transfer components "G" are connected. The G's represent the linear or non-linear heat transfer by conduction (in the soil), by convection and by radiation. On the bottom right side the heat flow is seen to enter a regular conductance - capacitance network, representing the compartimented soil.
The left side of the bond graph is the vapour model. There the mass balance of the vapour in the inside air is represented by the vapour capacity C, with its associated state variable e_{air}. An incoming flow source SF and an outgoing G represent the vapour which comes in and goes out by ventilation.

The coupling between the vapour and thermal parts of the model involves evaporation or condensation at the soil surface (lower coupler) and at the plant surface (middle coupler). At the glassroof (top coupler) only condensation takes place. The couplers are represented by transducers (TD). Due to the interactive nature of the energy exchange each TD represents two relations: one between the vapour pressure and its associated temperature and one between the vapour mass flow and the corresponding latent heat flow.
The stomatal behaviour is incorporated in the non-linear G_{stom} component.

A more detailed description of the bond graph model and its simulation is given in a previous paper (Bot et al., 1976). The THTSIM programme accepts the bond graph structure in a simple way. When the constant or time dependent parameters of the components and the simulation control data (timing, plot outputs) are specified the numerical or plotted response can be obtained. The user keeps all the time in touch with components and a structure having a physical meaning.

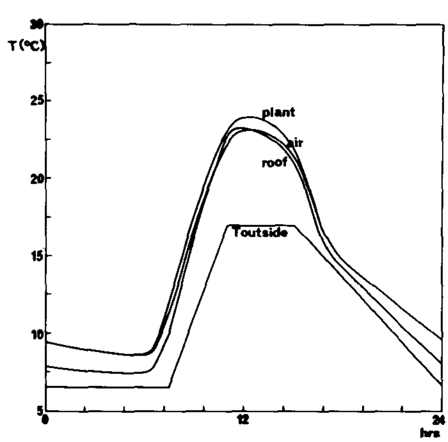

fig. 2. Some temperatures over 24 h. in an unheated glasshouse

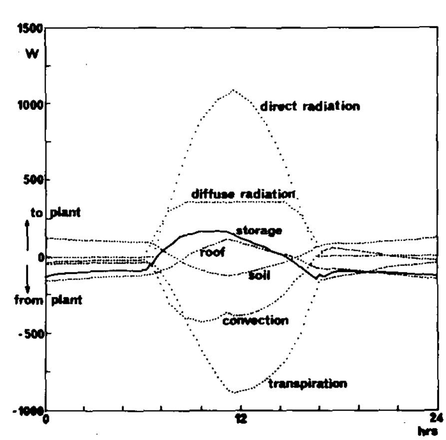

fig. 3. Terms of the energy balance of the plant compartment

Simulation results are shown in figs. 2, 3 and 4. The temperatures of the outside air, the cover-, the air-, the plant- and the upper soil-layer compartment are given in fig. 2. The glasstemperature has a value between that of the inside air and outside air at night, by day it has nearly the same value as the inside airtemperature though the outside heat transfer coefficient is much higher than the inside one. This is caused by the high rate of radiation absorption. By day, the plant temperature is a few degrees higher than the air temperature, at night they are nearly the same. The adjustment of the plant temperature is given in fig. 3. In the daytime, incoming radiation is mainly compensated by transpiration. The thermal radiation to and from the soil and the glass nearly compensate each other. Also for varying weather conditions simulations can be made.

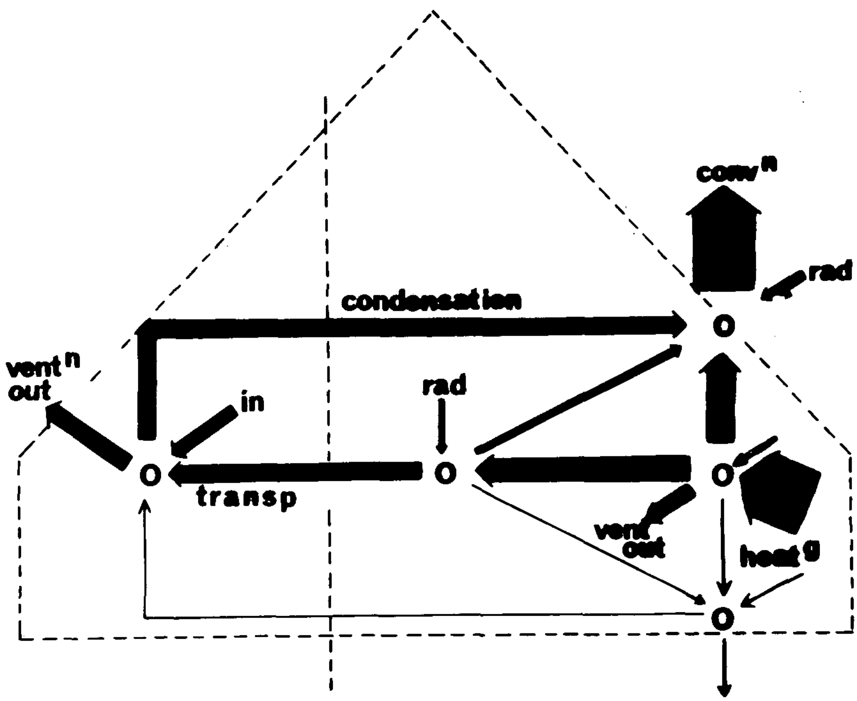

Fig. 4. Temperatures and heat flows during a cold rainshower

Fig. 4 shows the heat flows and temperatures at one moment during a cold rainshower. It is represented in a formalised bond graph way (Sankey diagram), constructed from the printer outputs.
This type of diagram gives a good insight in the heat and vapour flows in the system under varying conditions.

5. Conclusions

Optimal plant growth is formulated as a hierarchial control problem with three control levels. A physical climate model is promising for application in a control algorithm for both heating and ventilation. This model is kept simple because it is applied in a closed control loop and it is not yet possible to quantify accurately all involved transport processes. By sensitivity analysis, the sensitive parts of the model can be located. For control in the second level, not only plant exchange but also plant processes have to be included in the model. Presently, plant behaviour can be described as a function of the environmental parameters and used in the simulation of the microclimate (Goudriaan, 1977). At the third level, a lot of horticultural knowledge is available, but only in static form. In the systems approach dynamic optimization has to be performed. A first attempt is published recently (Challa, 1977).

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