CONTROL AND MODELLING OF VERTICAL TEMPERATURE DISTRIBUTION IN GREENHOUSE CROPS

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Abstract

Based on physical transport processes (radiation, convection and latent heat transfer) a model has been developed to describe the vertical temperature distribution of a greenhouse crop. The radiation exchange factors between heating pipes, crop layers, soil and roof were determined as a function of the vertical distribution of the leaf area of the crop. To validate the model a series of experiments was performed with a tomato crop under a range of ambient night-time conditions, including differences in LAI and position and temperature of two pipe heating systems.
The local effects of increased pipe temperatures on leaf temperature appear to be rather limited as well as on the distance over which significant effects occur.
The model can be used to predict crop temperature distribution as a function of the position and temperature of the heating pipe. This can lead to a better control of crop development and a more efficient use of energy.

1. Introduction

The presence of a cover, characteristic of greenhouses, causes, a change in the climate conditions as compared to those outside: radiation and air velocity are reduced, temperature and water vapour pressure of the air increase, and fluctuations in carbon dioxide concentration are much stronger. Each of these changes has its own impact on growth, production and quality of the greenhouse crop (Bakker, 1995). The final target of environmental control is to optimise the crop production. So far most control actions in greenhouses are based on temperature and humidity measurements made at a representative height, either fixed or near the growing point of the crop (Gieling and Schurer, 1995). The presence of independently controllable heating systems enables local crop heating to influence the crop development. This results from the fact that temperature has a direct effect on the sink strength of the individual organs of the plant (Marcelis and de Koning, 1994, de Koning, 1994). Furthermore the rate of development (leaf unfolding, flowering) in many crops responds, over a wide range of temperatures, linearly to temperature (*e.g.* De Koning, 1994; Karlsson, *et al.*, 1991). Consequently local crop heating can be used to control biomass partitioning or to enhance the development.

Although for crop control the use of heating systems near the growing point of the crop might be preferred, this generally results in an increase of energy loss from the greenhouse due to increased thermal radiation exchange between the heating system and the roof (Bot and Van de Braak, 1995). To optimise the position and use of independent heating systems from the viewpoint of energy-efficiency, as a first step, a model was developed to predict the vertical crop temperature distribution under night time conditions at a given leaf area index and distribution.

2. Materials and methods

2.1. Model description

A two-dimensional layer model has been made of the greenhouse and crop. It consists of a top layer representing the greenhouse roof, a bottom layer representing the greenhouse soil and in between a number of layers representing the tomato crop and greenhouse air. The heating pipes are represented by two layers: one for the pipe rail system (lower heating system) and one for the upper heating system (in the Netherlands called growing pipe). For each cluster of fruits, the pertaining leafs (up to the height of the cluster) are presented by a crop layer. The air is represented by a number of layers equal to the crop.

2.1.1. Radiation

A separate computer program has been developed to determine the radiative exchange factors between the various layers depending on the number of fruit clusters (crop layers), their height above the soil and their mutual distance and the position of the heating pipes with respect to soil and crop. In order to determine the radiation exchange factors first the mutual view factors of crop layers, soil and roof are calculated. The radiation flux emitted by a surface i is determined by the emissivity (ε_i), area (A_i) and temperature (T_i). The view factor, F_{ij}, determines which part of the total radiation from surface i falls directly on surface j. The fraction of the radiation directly from surface i absorbed by surface j equals $F_{ij}\varepsilon_j$. Surface j also receives indirectly radiation from i, via reflections at the surfaces k. B_{ij} is the absorption factor representing the fraction of all radiation from surface i which is absorbed by surface j, this absorption factor can be written for opaque surfaces as (Vollebregt and Van de Braak,1994)

$$B_{ij} = F_{ij}\,\varepsilon_j + \Sigma_k\, F_{ik}\,(1\text{-}\varepsilon_k)\, B_{kj} \qquad (1)$$

Where Σ_k is the sum of the reflections at all surfaces (k) towards j.
The net radiation exchange q between the surfaces i and j can be written as :

$$q_{ij} = \varepsilon_i\, A_i\, B_{ij}\, \sigma(T_i^4\text{-}T_j^4) \qquad (2)$$

In which σ is the Stefan-Boltzman constant and the term $\varepsilon_i\, A_i\, B_{ij}$ is called the radiation exchange factor. If ε_i is high, as often is the case in greenhouses, the second term of equation 1 can be neglected and B_{ij} is approximately $\varepsilon_j\, F_{ij}$.
The viewfactors between the various layers(i) and the heating pipes (j) are calculated by:

$$F_{ij} = (\mathrm{atan}((Z/X) - \mathrm{atan}(Y/X))/(Z - Y) \qquad (3)$$

With X = c/d, Y = a/d and Z = b/d in which a,b,c and d are given by figure 1. Five crop rows at either side of a heating pipe are taken into account.
The view factors between the crop layers are determined by using the leaf area index (LAI) of the individual layers as intercepting surfaces for radiation leaving a given crop layer. For instance the view factor of the soil to the fourth crop layer is:

$$F_{soil,crop4} = (1\text{-}LAI_{c1})\,(1\text{-}LAI_{c2})\,(1\text{-}LAI_{c3})\,LAI_{c3} \qquad (4)$$

Where LAI_{cx} is the Leaf Area Index of crop layer x.

The resulting view factors are corrected to account for the view factors to the heating pipes using the fact that the sum of all view factors of a surface is 1.

2.1.2. Convection

The convective heat exchange coefficient α between greenhouse air and crop for each individual air-crop layer is determined according to Stangellini (1987) by :

$$\alpha = \rho\, c_p\, r_e^{-1} \qquad (5)$$

With the external resistance r_e being:

$$r_e = 1174\, L^{0.5}\, (L\, |T_{crop} - T_{air}| + 207u^2)^{-0.25} \qquad (6)$$

Where L is the characteristic length of the leafs in a given layer (between 1 and 7 cm) and in which the air velocity (u) for leafs below the position of the heating pipes is estimated, according to Stanghellini (1987), at 0.05 ms^{-1} and above the position of the heating pipes at 0.15 ms^{-1}.

2.1.3. Evaporation

The latent heat exchange Q_c to the greenhouse air by evaporation of each crop layer is calculated using the general formulation of Stanghellini (1987):

$$Q_c = 2\, LAI_c\, \rho\, c_p\, \Delta p\, (\gamma(r_i+r_e))^{-1} \qquad (7)$$

Where r_i is the internal leaf resistance and Δp the vapour pressure deficit. The following parameters for night time conditions were used:

$$r_i = 685.5\, r_{\Delta p}\, r_t\, r_{co2} \qquad (8)$$
$$r_{\Delta p} = \text{minimum of } (3.8 \text{ and } (1. + 5.2\ 10^{-6}\, \Delta p^2)) \qquad (9)$$
$$r_t = 1 + 0.005\, (T_{crop}-273.15-33.6)^2 \qquad (10)$$
$$r_{co2} = 1+1.11\ 10^{-11} \times (CO_2-200)^2 \qquad (11)$$

With T_{crop} the leaf temperature and CO_2 is the carbon dioxide concentration of the ambient air.

The model uses the temperatures of the soil, roof, greenhouse air and heating pipes and the average humidity of the greenhouse air as boundary values. Via the energy balances of the crop layers, in which the transpiration, convective heat exchange and radiative exchange are incorporated, the vertical temperature distribution of the crop is calculated.

2.2. Experimental set-up

The experiment was performed in a glasshouse compartment at the Research Station for Greenhouse Floriculture and greenhouse vegetables in Naaldwijk (PBG).

The compartment was 283 m^2 (5 × 3.2 m span by 17.7m) with a gutter height of 4.2 m and a concrete floor (thickness 7 cm).

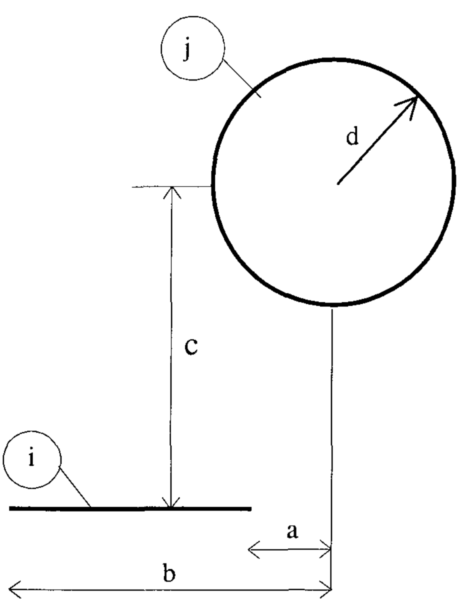

Figure 1 Configuration for view factor calculation of surface i to pipe surface j

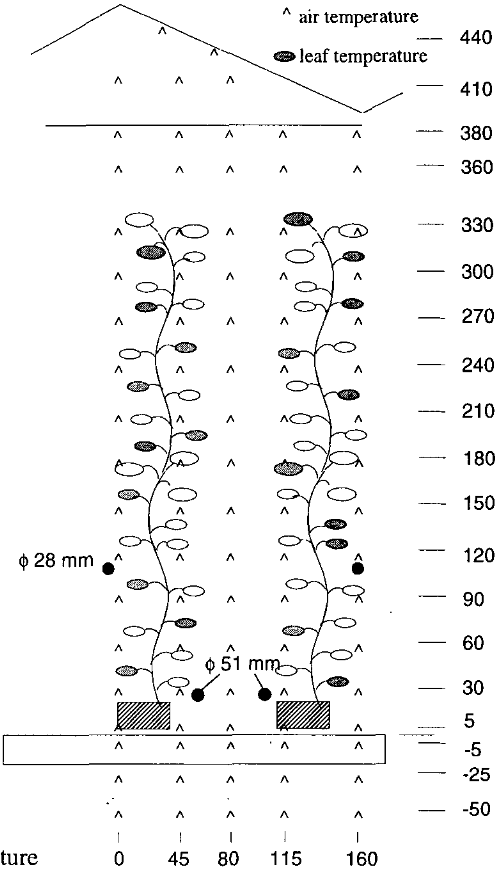

Figure 2 Layout air and leaf temperature thermocouples in the measuring area

A tomato crop was grown on rockwool, planting date: 20 December, plant density: 2.8 plants m^{-2}. The setpoints were for heating 18.5/17.5 °C at day/night and for ventilation 20/19 °C at day/night. No minimum pipe temperature settings or additional humidity setpoints were applied.

In the compartment one heating system, the pipe-rail (four ϕ51 mm pipes per 3.2 m span) was located at 15 cm above the floor with alternating distance between the pipes of 40 and 80 cm. The second heating system (two ϕ28 mm steel pipes) was located in sequential experiments at three heights: 0.40, 1.50 and 2.5 m respectively. This 28 mm heating system was used prior to the pipe-rail system in the environmental control. To reach the air temperature setpoint, first the 28 mm (growing pipe) system was used up to a maximum water temperature of 60 °C. Only if the heating capacity of this system was insufficient to maintain the air temperature setpoint, the 51 mm system (pipe-rail)provided the additional required heat input.

The position of the 28mm pipe was changed with a frequency of one week over a total period of 2.5 months. In total the positions 0.4, and 2.5m were maintained for two weeks and the 1.5 m position for 4 weeks.

2.2.1. Leaf area

During the experiment from March to June the leaf area between individual trusses was measured five times from destructive measurements. For this purpose plants were selected from the area just next to the measuring area of the leaf and air temperatures.

2.2.2. Temperatures

The air and leaf temperatures were measured using thermocouples: 86 for air and 60 for leaf temperatures (6 plants with 10 sensors per plant).The roof temperature was measured at two locations and the soil temperature at 15 locations at depths of 5, 25 and 50 cm. The location of the measuring points is presented in figure 2.

For the leaf temperature measurements 250 micron thermocouple wire was used. The sensors were connected to a data acquisition system with a sample time of one minute. Data averaged over five minutes were stored automatically through a data-net on a central computer system at the PBG (Bakker, *et al.*, 1988). The measurements took place over the period from 16 February until end of April. For the leaf temperature measurements, the thermocouples were frequently repositioned as the crop grew and leaf positions and position of the heating system changed. Three times a week (before sunset and at sunrise) it was checked whether the thermocouples still made contact to the leaf and the leaf height was measured.

2.2.3. Data processing

For parameterisation of the model for the various positions of the heating system a selection was made from the overall data sets collected. For a good comparison of the night situations the following selection criteria were used:

Roof ventilators closed, outside temperature between 6 and 6.5 °C, time between 6.00 pm and 6.00 am, air temperature at control sensor: between 17.3 and 17.5 °C, temperature of the 51 mm system less than 45 °C, temperature of the 28 mm system higher then 55 °C.

Furthermore all data of which was noticed that the contact between thermocouple and leaf was lost, were removed from the data sets.

3. Results

3.1. Leaf area measurements

The number of trusses varied between 6 and 9, the LAI from 3 to 4.2 and the truss distance between 0.22 and 0.30 m. Figure 3 presents the leaf distribution as fraction of the total LAI for 4 development stages of the crop. The increasing percentage of the first truss of the 7 leaf layers is a affect of leaf cutting situations.

3.2. Air and leaf temperatures

For the selected datasets, an average was calculated for air and leaf temperatures at the various heights over a period of one week.

In figure 4 the averaged air and leaf temperatures of week 15, 16 and 17 after planting are presented as a function of the height for the three pipe positions.

The long term effect of local heating on the air temperature distribution is rather limited. Just above the growing pipe the air temperature increases between 0.2 and 0.3 °C as shown in figure 4 (a). The effect of local heating on leaf temperatures (figure 4 (b)) is somewhat more pronounced. For a pipe position at 1.5 m the average leaf temperature at 1.5 m is about 0.5 °C higher, while for a pipe position at 2.5 m, the leaf temperature at 2.5 m is almost 0.4 °C higher compared to the other pipe positions.

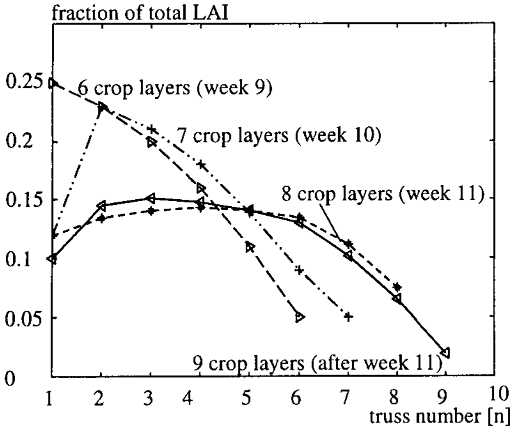

Fig. 3. Leaf after distribution 8,9,10 and 11 weeks after planting

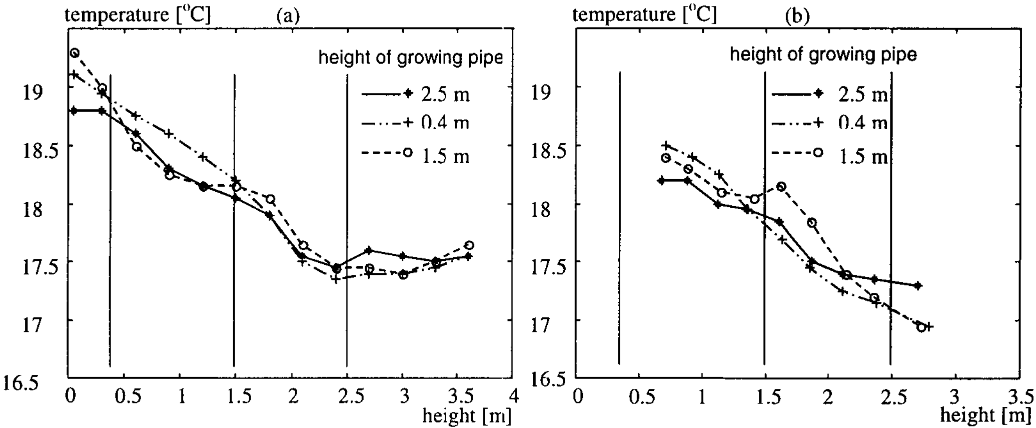

Figure 4 Measured air temperature distribution (a) and leaf temperature distribution (b) in week 15, 16 and 17 after planting for 3 growing pipe positions.

3.3. Model validation

The measured average leaf temperatures have been compared with the values the model predicts. Figure 5 shows that both for the position of the growing pipe at 0.4 m (a) and for the situation with the growing pipe at 2.5 m (b), the predicted temperature profile is corresponding with the measurements. The crop temperatures are both in measurements and predictions below the air temperature.

As the accuracy of the measured air temperature (is ± 0,2 °C) and due to the error in RH measurements, the simulated crop temperature will have an error of at least 0,2 °C. The measured crop temperature has also an error of 0,2 °C. Figure 5 shows that prediction and measurement coincide within the accuracy's mentioned

4. Discussion

Literature provides very little detailed information on vertical air and leaf temperature distribution in greenhouse crops as a result of heating pipe position, especially in tomato crop. Our experiments show that the greenhouse air temperature above the crop is lower than in the crop in case the heating pipes are below the top of the crop. This is in agreement with the observations of Winspear (1978) and Yang (1995), although the latter measured in another type of crop (potted Chrysanthemums). In the winter period Yang found that leaf temperatures were in general below the air temperature. The same tendency was found in our experiments.

The possibility to influence crop temperatures locally appears to be rather limited (0.5 °C) if only part of the heating system (growing pipe) is used for this purpose.

As the predicted temperature profile is corresponding with the measurements and the values differ only a few tenths of a degree, the model developed appears to be suitable to predict the vertical temperature distribution of a tomato crop, provided the vertical air temperature distribution is known.

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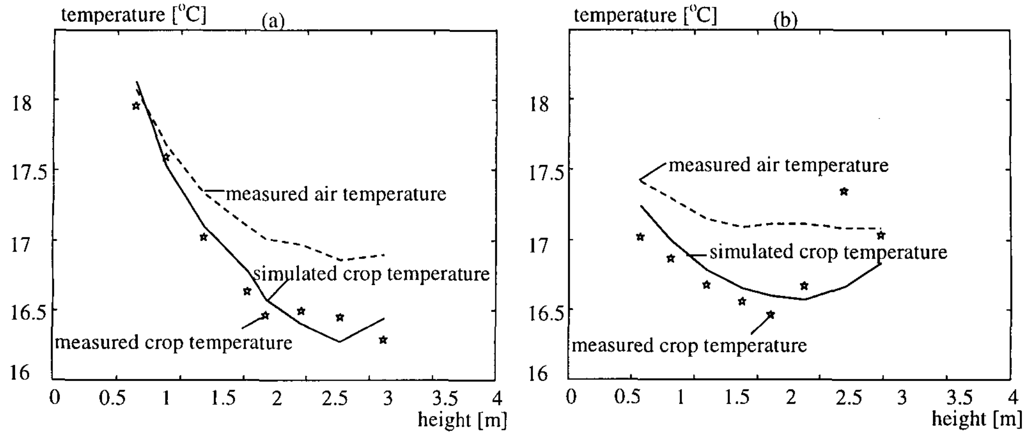

Figure 5 Measured air and leaf temperature and simulated leaf temperature for a growing pipe position of 0.4 m (a) and 2.5 m (b).