A MODEL OF GREENHOUSE HUMIDITY SUITABLE FOR CONTROL OF CROP PROCESSES

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Abstract

A physical model of humidity within a greenhouse was developed, whereby ambient vapour concentration resulted from the balance of three fluxes: crop transpiration, ventilation and condensation at the cover. The present paper describes the application of such a model in the greenhouse climate control. Two examples are shown in order to demonstrate that it is possible to deduce set points for climate actuators from desired levels of humidity-related crop processes such as transpiration or dew forming. Within the selected range, the final choice of set points can be based on cost-benefit analysis. This could prevent useless ventilation and heating and consequently save energy. Accordingly, modern greenhouse climate management could be largely improved by incorporating physical models in order to deduce set points for actuators (mainly temperature and ventilation) directly from the desired level of a crop process.

1. Introduction

The application of automatic control equipment and a better understanding of the processes behind greenhouse climate have considerably expanded the possibility for the grower to control the climate in the house. The aim of the grower is to achieve optimal environmental conditions for the crop. The variables routinely controlled in a greenhouse are temperature, humidity and CO_2 content of the air. Temperature is controlled through heating and ventilating. Humidity can be increased by fogging systems, that are usually applied in regions with relatively dry climates, but seldom in moderate climates like in the Netherlands. Consequently fogging will not be considered here, although the present work can be easily adapted to include both fogging and dehumidification. Since dehumidification systems are seldom used, lowering of humidity is achieved by ventilation only, or by simultaneous heating and ventilation. The latter procedure is the most widespread technique to remove excess vapour in the Netherlands. The CO_2 enrichment is dependent on the measured concentration of CO_2 in the house.

Obviously, the control loops of the different variables may affect each other. Undesirable situations may occur where, for instance, heating or CO_2 enrichment take place during periods of ventilation. In addition, the many control set points that can be adjusted and established along different paths complicate the assessment of the 'optimal' set of values for the controlled variables. In practice, many growers adjust control set points according to their experience or simply to prevent extreme conditions for the crop. In such cases one can hardly speak of 'optimal' environmental control. For instance, with respect to the effect of humidity, it is well known that growth and production of greenhouse vegetables are affected by ambient humidity (Bakker, 1991). Presently, however, the control of humidity in commercial

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greenhouses in moderate climates is often restricted to: 1. avoiding dew forming on the crop in order to prevent the incidence and development of fungal diseases (Hand, 1988); and 2. to prevent too small transpiration rates, which have been linked to calcium deficiency in growing leaves (Aikman and Houter, 1990) and unsatisfactory crop development (Holder and Cockshull, 1990).

In practice, one can translate both these purposes into preventing a 'too high' humidity within the greenhouse. The technique of heating and ventilating to achieve this goal is responsible for a big fraction of the energy requirements in Dutch greenhouses (Bakker, 1994). Both the objectives of limiting dew formation and of achieving a desired transpiration rate are related to humidity. The linkage, however, creates some difficulties. For example, the extent to which one can lower humidity to limit dew formation is affected by the increase in transpiration caused by any reduction in humidity (Matthews and Saffell, 1981).

In this article it is demonstrated that application of a humidity model leads to direct control of crop processes like dew forming and transpiration. This can considerably improve the current control of humidity, since proper actuators set points can be deduced from the desired value of the process.

2. Short description of the model

Models for the calculation of evapotranspiration and ventilation have been developed respectively by Stanghellini (1987) and De Jong (1990). The combination of these works into a humidity model is described in detail in Stanghellini and De Jong (1995). The present paper resumes, in short, the main principles of the model and presents some new applications for the control of crop processes.

A model fit for the control of humidity-related crop processes has to account for the environmental effect on the vapour content of the air in such a way that the impact of regulated variables (like air temperature and ventilator opening) can be split from the effect of weather. The evapotranspiration flux from the crop, ***E***, is the main source of vapour in a greenhouse whereas vapour removal takes place through both condensation, ***C***, and ventilation, ***V***, so that the following balance equation holds:

$$h\dot{\chi}_a = \boldsymbol{E} - \boldsymbol{C} - \boldsymbol{V} \qquad \text{kg m}^{-2}\ \text{s}^{-1} \quad \textbf{(1)}$$

where h (m) is the ratio of the greenhouse volume to its ground area, that is, the mean height of the house, and χ_a is the mean vapour content of the air within (kg m—3), all the fluxes being referred to unit ground area. The model calculates the temperature of the crop, the humidity of the greenhouse air and thereupon the vapour fluxes due to ventilation, condensation and transpiration. The required input variables (with the exception of the cover temperature) are routinely recorded by current climate control systems.

For the purpose of the present paper it will be sufficient to say that all three vapour fluxes in Eq. (1) were described formally by a transfer equation, that is, as a gradient of vapour concentration times a conductance (g, s m—1) typical of the flux. Accordingly, the vapour balance of the greenhouse air, Eq. (1), was re-written as follows:

$$h\dot{\chi}_a = g_{trans}(\chi_c - \chi_a) - g_{cond}(\chi_a - \chi^*_r) - g_{vent}(\chi_a - \chi_o) \qquad \text{kg m}^{-2}\ \text{s}^{-1} \quad \textbf{(2)}$$

where the subscripts *c, r* and *o* refer to vapour concentration at the canopy, cover and outside, respectively, and the superscript * indicates saturation. Of course, the second term in Eq. (2) is omitted if $\chi_a < \chi_r^*$ and the cover is dry. Eq(2) can be rearranged, by grouping the coefficients of ambient vapour concentration, χ_a, and the terms independent from the latter:

$$X - g_{tot}\chi_a - h\dot{\chi}_a = 0 \qquad \text{kg m}^{-2}\,\text{s}^{-1} \quad \textbf{(3)}$$

Here g_{tot}, an apparent cumulative transfer conductance, is defined by:

$$g_{tot} \equiv g_{trans} + g_{cond} + g_{vent} \qquad \text{m s}^{-1} \quad \textbf{(4)}$$

whereas *X*, the flux that would occur if the air in the house were completely dry, is:

$$X \equiv g_{trans}\chi_c + g_{cond}\chi^*_r + g_{vent}\chi_o \qquad \text{kg m}^{-2}\,\text{s}^{-1} \quad \textbf{(5)}$$

Actually, Stanghellini and De Jong (1995) have shown that the conditions for an analytical solution to the differential equation (3) are only approximately met here. They have shown, however, that ambient vapour concentration at any time, *t*, can be very nearly calculated through the formal solution of Eq (3):

$$\chi_a(t) = \frac{X}{g_{tot}} - \left(\frac{X}{g_{tot}} - \chi_a(0)\right) e^{-\frac{t}{\tau}} \qquad \text{kg m}^{-3} \quad \textbf{(6)}$$

and τ, the time constant of the system, is calculated through:

$$\tau = h/g_{tot} \qquad \text{s} \quad \textbf{(7)}$$

A typical diurnal course of the time constant is given in Fig. 1, that was calculated with data of a rather dark day, with fairly uninterrupted condensation and some afternoon ventilation, for a 3.5 m tall glasshouse. From the effect of three simulated leaf areas it can be deduced that a non-fully developed crop causes the system to be slower. In the daytime the time constant will not normally be much larger than 5 minutes. At night, however, as the figure shows, it can take several minutes for any change in conditions to show through ambient humidity. Given the response time of a heating system and of air temperature, any climate control algorithm should take into account the time-dependent part of Eq. (6), in order to avoid overshooting.

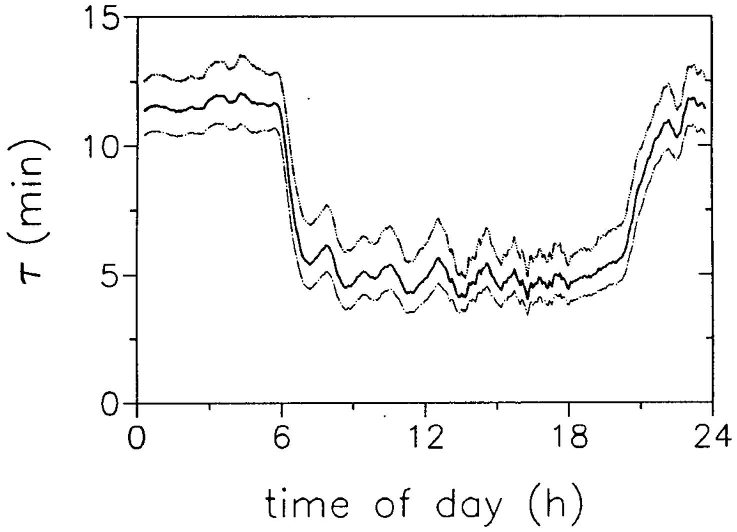

Figure 1. The time constant of humidity in a glasshouse with 3.5 m gutter height, calculated from measured data of a spring day for three leaf area indices (LAI), respectively, 2 (top), 3 (middle) and 4 (bottom).

3. Applications

3.1. Control of transpiration and prevention of dew

A couple of possible applications of this model will be discussed here. Most modern greenhouse climate control systems include a routine with the dual purpose of sustaining a "minimal" transpiration rate and of avoiding dew forming on parts of the crop. This is enacted in practice by pre-selecting a humidity boundary (either a ceiling on relative humidity or a threshold on saturation deficit) and controlling heating and ventilation in order not to exceed such a boundary. However, the intended result (which is by no means warranted by such a procedure), can be achieved by deriving the required setpoints (heating and ventilation) directly from a required "minimum" transpiration level and an admitted chance of dew forming.

With respect to latter, even with a mean canopy temperature above dew point, there can be local dew forming on some (colder) parts of the foliage, fruits or stem. Controlling the climate in such a way that this should not happen requires an estimate of the temperature distribution within the crop. In order to get some insight, profiles of leaf temperature of a glasshouse tomato crop were measured by six series of five thermocouples each, held touching the lower surface of leaves, at three levels in the canopy and with various orientations. Resulting standard deviations are shown for instance in Fig. 2, for two days (a rather dark day and a leaf area index, LAI, of 3 and a sunny one and a LAI of 1.5). It can be seen that the night-time standard deviation of leaf temperature was rather constant in our experiments, 0.75°C being roughly the upper limit.

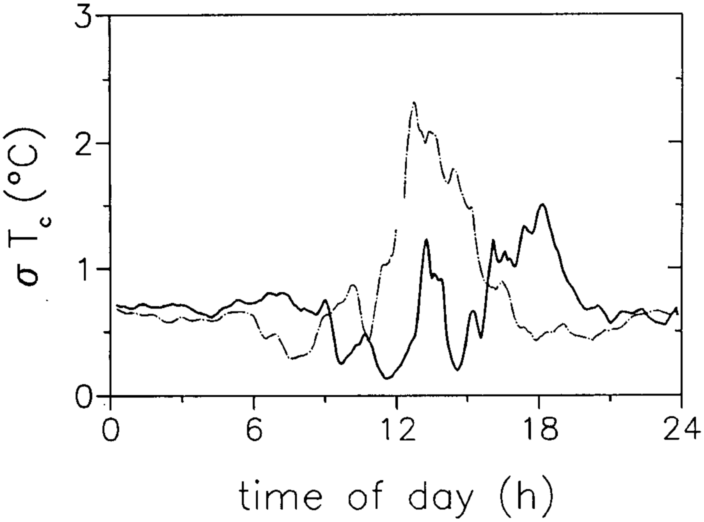

Figure 2. Daily course of the standard deviation of measured leaf temperature at six levels and orientations in a tomato canopy for, respectively, a cloudy day and a LAI of 3 (thick line) and a sunny day and a LAI of 1.5 (broken line).

For the sake of the present example, let's assume that the temperature distribution within the crop would be normal and that 0.75°C would indeed be its standard deviation. Then, at any time, some 1% of the crop would have a temperature differing, in either direction, by more than three standard deviations (2.25°C) from the mean. Now let's also presume that the model gives a good estimate of the mean temperature of the crop. Then one can stipulate, that in order to ensure that dew could form on less than about 0.5% of the crop, the calculated crop temperature has to exceed dew point by at least 2.25°C at night-time. Of course, non-uniformity of the water vapour concentration of the air could increase the percentage possibly wetted. This effect has now not been taken into consideration, but in practice one could take account for it by choosing a lower chance of dew forming.

Fig. 3 shows how the locus of the setpoints compatible with both a given threshold transpiration rate and a ceiling on chance of dew forming can be deduced from the present model, in the specific case of a relatively warm autumn night, as specified in the caption.

3.2. Use of a fan

As a second example, let us explore the use of air-recirculation fans. Although these are often installed with the aim of maintaining uniform climatic conditions, a possible outcome is an increase of the transpiration rate of the crop, through a more efficient removal of vapour from the leaf boundary layer (Fernandez and Bailey, 1994).

For instance, under cloudy conditions (150 W m^{-2}), transpiration in a closed house with inside air temperature about 19 °C and air velocity 0.06 m s^{-1} would be only 15 g m^{-2} h^{-1} (Fig. 4, point A). A transpiration rate of, say, 25 g m^{-2} h^{-1} would be ensured by heating (B) or ventilating (C), or a combination thereof. Figure 4 shows that a fan enhancing air movement to 0.5 m s^{-1} would warrant the same result with less expensive set points (points B' and C', respectively). In addition, from the same figure it may be seen that a further increase of air velocity would be only marginally beneficial. Therefore, assignment of cost and benefits to actuators set points, such as ventilator opening, air temperature and velocity may lead to the most economic choice of set points that would warrant the intended result.

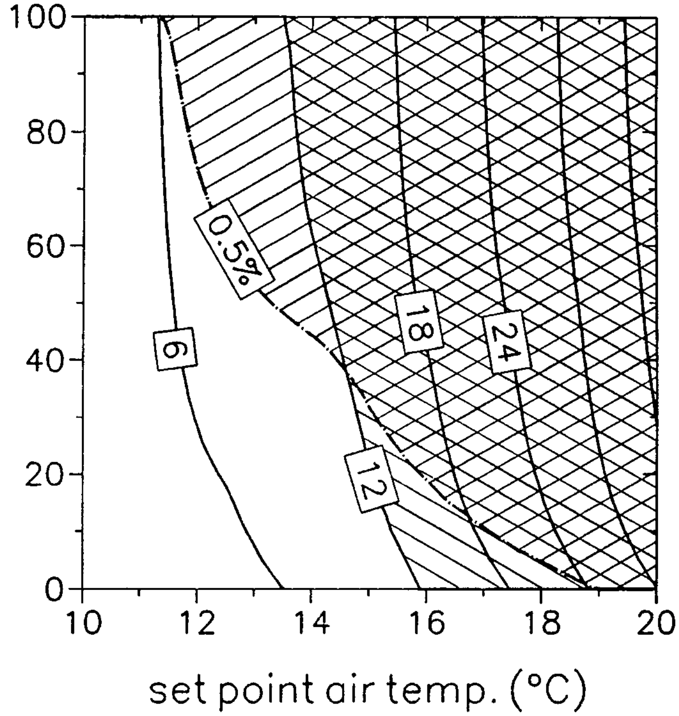

Figure 3. *Full lines: the transpiration rate,* g m^{-2} h^{-1}, *following from any combination of air temperature and ventilators opening (as percent of the largest angle, here 11°), calculated for the following weather conditions: nighttime; outdoor temperature 10°C; relative humidity 85% and wind speed 1* m s^{-1}. *Air movement within the house is 0.06* m s^{-1} *and leaf area index 3. The broken line is the boundary of 0.5% chance of dew forming. The shadings* ▨▧▩ *represent respectively: less than 0.5% chance of dew; transpiration rate larger than 12* g m^{-2} h^{-1}*; and the intersection of both conditions.*

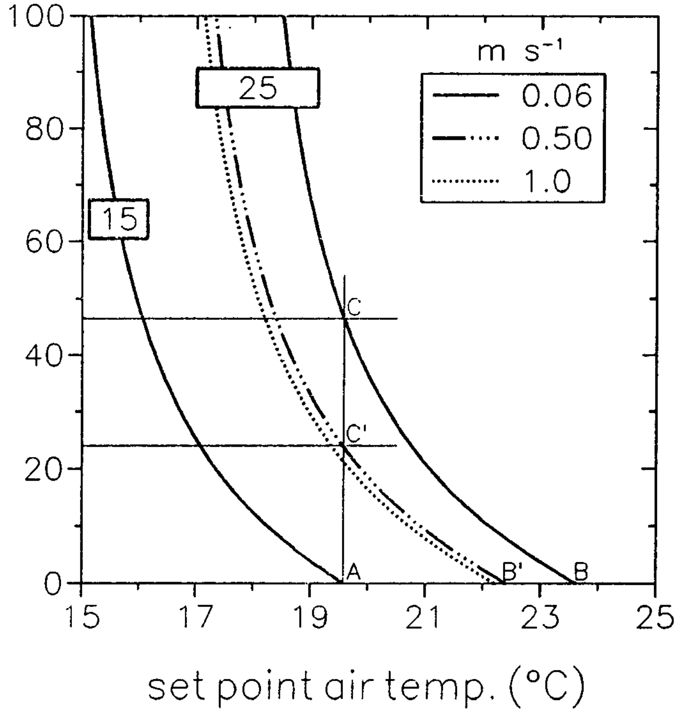

Figure 4. *The locus of the set points that would give a transpiration rate of 15 and 25* g m^{-2} h^{-1}, *respectively (full line), calculated for the same conditions as Fig. 3, except that sun radiation is 150* W m^{-2}. *The broken lines represent the set points that would result in a transpiration rate of 25* g m^{-2} h^{-1} *as well, were air speed in the house 0.5 or 1* m s^{-1}, *as indicated.*

4. Conclusion

The average grower has two instruments available for controlling the climate: heating and ventilation. Attaining a desired set point of humidity is complicated by the many feed backs in the vapour balance of the greenhouse system. Both examples shown above demonstrate that application of a humidity model would allow a control algorithm to select the locus of actuators set points directly from the humidity-related crop process one wishes to control, such as transpiration and dew forming. Within the selected range, the final choice of set points can be based on cost-benefit analysis. This could prevent useless ventilation and heating and consequently save energy.

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