MODELLING AND SIMULATION IN GREENHOUSE CLIMATE CONTROL

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Abstract

A new class of "general" models is presented for greenhouse climate control, incorporating soil temperature as an essential variable. The general models are demonstrated to fit accurately to measured data especially for high frequency perturbations. The new models offer new opportunities for simulation as well as analysis and synthesis of climate controllers.

1. Introduction

The traditional point of view to climate control of greenhouses is that the grower acts like an operator, manipulating valve settings and ventilation window apertures. To distinguish the operators approach from a more formal problem oriented one, the term GCFC (Greenhouse Climate Feedback/Feedforward Control) was introduced (Udink ten Cate, 1982, 1983).

In earlier work simple GCFC-models have been proposed for the greenhouse inside air temperature control (Udink ten Cate, 1983, Udink ten Cate et.al., 1984). The models describe small and relatively high frequency perturbations with respect to a slowly time-varying working-point. These perturbation models are readily formulated as transfer functions of which the parameters are related to heating-load coefficients (k-values) which are widely available. As a result, transfer functions are readily established for arbitrary greenhouses.

Control loops can be analyzed and synthesized with the perturbation models. However, since a greenhouse is an "open" structure with respect to outside weather conditions, the controller is as a rule saturated. Consequently not only the high frequency increments describing the control behaviour are of interest, but also the characteristics associated with large and slowly time-varying signal components.

In this paper combined transfer function GCFC models are presented which match the high frequency GCFC behaviour and the working point (Udink ten Cate, 1985a).

A drawback of the combined models is that the parameters do not directly follow from physical phenomena. To solve this shortcoming, a hypothetical general GCFC model is presented where both inside air and soil heat storage are modelled. The general model can be validated directly to k-values, as opposed to the perurbation models mentioned above where some k-values differ by a factor 2-3 from the physical ones. It is seen that the general model gives an excellent fit, both for low-frequency and high frequency phenomena.

2. Perturbation models

Perturbation GCFC models for the greenhouse inside air temperature θ_g [^{0}C] are based upon an indealized model of the greenhouse, consisting of a single energy storage element

$$C_{p,g}\frac{d\theta_g}{dt} = -q_v(t)c_{p,air}\rho_{air}(\theta_g(t)-\theta_a(t)) - \frac{1}{R_{p,r}}(\theta_g(t)-\theta_a(t)) +$$

$$+\frac{1}{R_{p,h}}(\theta_h(t)-\theta_g(t)) + \eta_p\,\phi_S(t) \qquad (1)$$

Here $q_v(t)$ [$m^3 s^{-1}$] is the air exchange rate, θ_a [^{0}C] is the outside air temperature, θ_h [^{0}C] is the average water temperature of the heating system, controlled by a three-way mixing value mixing return water with temperature θ_r [^{0}C] and water from the main boiler θ_f [^{0}C] leading to water with temperature θ_m [^{0}C] going into the greenhouse. ϕ_S[W] is the solar radiation outside the greenhouse. Of the parameters in eqn.(1) the index p means that they belong to the perturbation model. $C_{.,g}$ [J/K] is the greenhouse heat capacity, $c_{p,air} \simeq 10^3$ [$Jkg^{-1}K^{-1}$] at constant pressure, $\rho_{air} \simeq 1.2$ [$kg\ m^{-3}$], $R_{.,h}$, $R_{.,r}$ [KW^{-1}] are thermal resistances, and η_p is a fraction [0,1]. Eqn.(1) is normalized per unit greenhouse ground area A_g [m^2] leading to $C^*_{p,g} \triangleq C_{p,g}/A_g$; $q^*_v \triangleq q_v/A_g$ etc. The normalized ventilation term following from eqn.(1) is

$$c_{p,air}\rho_{air}\,q_v(t)/A_g = 1200.\bar{h}_g\,q_v(t)/V_g = \zeta\bar{h}_g\,S_v(t) \qquad (2)$$

where the ventilation rate per hour $S_v(t) \triangleq 3600.q_v(t)/V_g$[$h^{-1}$], the constant $\zeta \simeq 1/3$, and $\bar{h}_g \triangleq V_g/A_g$ is the average height. Linearizing eqn. (1) around a nominal working point in terms of perturbations or incremental variables defined by $\tilde{\theta}(t) \triangleq \theta(t)-\bar{\theta}$ leads to

$$C^*_{p,g}\frac{d\tilde{\theta}_g}{dt} = -(k^*_{p,v}+k^*_{p,r}+k^*_{p,h})\tilde{\theta}_g(t) + k^*_{p,h}\,\tilde{\theta}_m(t-\tau_{d,h}) +$$

$$+\zeta\bar{h}_g(\bar{\theta}_a-\bar{\theta}_g)\tilde{S}_v(t-\tau_{d,v}) + \eta_p\,\tilde{\phi}''_S(t-\tau_{d,s}) \qquad (3)$$

where $\tau_{d,.}$ are dead times denoting the transport times in the greenhouse, $k^*_{p,v} \triangleq \zeta\,\bar{h}_g\bar{S}_v$, $\phi''_S \triangleq \phi_S/Ag$ [Wm^{-2}], θ_m replaces θ_h and θ_a is assumed to be constant ($\tilde{\theta}_a = 0$). Keeping the other incremental variables zero, from eqn.(3) transfer functions are readily derived, for example

$$H_{p,h} \triangleq \frac{\tilde{\theta}_g(s)}{\tilde{\theta}_m(s)} = K_{p,h} \frac{e^{-\tau_{d,h} s}}{\tau_{p,h} s+1} \tag{4}$$

with $\tau_{p,h} = C^*_{p,g}/(k^*_{p,v} + k^*_{p,r} + k^*_{p,h})$, $K_{p,r} = k^*_{p,h}/(k^*_{p,v} + k^*_{p,r} + k^*_{p,h})$. More details are found in Udink ten Cate (1983, 1985a, b). Indicative values are presented in table 1.

$k^*_{p,h} = 1.46(\bar{\theta}_m - \bar{\theta}_g)^{0.46}$	$\eta_p = 0.7$
$k^*_{p,r} = 30$	$\tau_{d,h} = 7$ min.
$k^*_{p,v} = S_v$	$\tau_{d,s} = 1$ min.
	$\tau_{p,s} + \tau_{d,s} = \tau_{p,h} + \tau_{d,h}$

$C^*_{p,g}/60 = 725$ (divided by 60 in order to give $\tau_{p,.}$ in min.)

Table. 1. Perturbation parameters for Naaldwijk glasshouse (Udink ten Cate, 1983)

3. Combined models

The perturbation models only describe high and relatively small increments with respect to a slowly time-varying working point. The working point itself can also be modelled. Using eqns (1-3) we arrive at

$$(k^*_{ss,h} + k^*_{ss,r})\bar{\theta}_g = k^*_{ss,h}\bar{\theta}_m + k^*_{ss,r}\bar{\theta}_a + \zeta\bar{h}_g(\bar{\theta}_a - \bar{\theta}_g)S_v + \eta_{ss}\phi_s''$$

The suffix ss denotes the steady state value of the parameters which follow from steady state conditions. Although in eqn.(5) only average values of the parameters are taken, slowly time-varying values can be described too.

With $k^*_{ss,h} = 1.0(\bar{\theta}_m - \bar{\theta}_g)^{0.46}$ ($k^*_{p,h}$ in table 1. is a linearized version) indicative values are presented in table 2.

Experiment	$k^*_{ss,r}$	$k^*_{p,r}$	$k^*_{p,r}/k^*_{ss,r}$	η_{ss}	η_p	η_p/η_{ss}
Night	9.9	29.7	3.0	-	-	-
Day	7.7	21.8	2.8	0.45	0.7	1.6

Table 2. Steady state parameters for Naaldwijk glasshouse (Udink ten Cate, 1983)

Combined models describe the working point given by steady state parameters as well as perturbations given by perturbation parameters. Details are given in Udink ten Cate (1985a, b). For the heating system transfer function the result is

$$H_{c,h} \triangleq \frac{\theta_g(s)}{\theta_m(s)} = K_{c,h} \frac{e^{-\tau_{d,h}s}(\tau_1 s + 1)}{(\tau_2 s + 1)(\tau_{sh} s + 1)} \qquad (6)$$

with $K_{c,h} = k^*_{ss,h}/(k^*_{ss,r} + k^*_{,h})$, $\tau_{c,h} = \tau_{p,h}$, $\tau_2/\tau_1 = k_{c,h}/k_{p,h}$ where τ_1 is chosen arbitrarily($\tau_1 \approx 2-3\tau_{p,h}$). Other transfer functions can be formulated in an analogous way.

4. General models

In this section a general model will be presented which uses a soil temperature θ [^{0}C]. This soil temperature is measured in the upper layer of greenhouse soil. For the validation of the parameters in this paper, however, θ_s and θ_{sc} have not been measured and are of a hypothetical nature. The normalized equations are

$$C^*_g \frac{d\theta_g}{dt} = \zeta\bar{h}_g S_v(t) \; (\theta_a(t)-\theta_g(t) + k^*_h(\theta_h(t)-\theta_g(t) + k^*_r(\theta_a(t)-\theta_g(t) +$$

$$+ k^*_s(\theta_s(t)-\theta_g(t)) + \eta\,\phi''_s(t) \qquad (7a)$$

$$C^*_s \frac{d\theta_s}{dt} = k^*_s(\theta_s(t)-\theta_g(t) + k^*_{sc}(\theta_{sc} - \theta\;(t))$$

Here θ_s [^{0}C] is the temperature of the upper layer of soil in the greenhouse, and θ_c is the constant temperature at deeper layers. k^*_s and k^*_{sc} are related normalized k-values. Note that the definition of θ_s is rather ambiguous, which is also true for C^*_s (how thick is the layer of soil to take into account). As a guidline C^*_s is based on 10-20 mm of soil. Rewriting eqns.(7) leads to

$$C^*_g \frac{d\theta_g}{dt} = -(k^*_v + k^*_r + k^*_h + k^*_s)\theta_g(t) + k^*_h\,\theta_m(t-\tau_{d,h}) + (k^*_v + k^*_r)\theta_a(t-$$

$$-\tau_{d,a}) + k^*_s\,\theta_s(t) + \eta\,\phi''_s\,(t-\tau_{d,s}) \qquad (8a)$$

$$C^*_\zeta \frac{d\theta_s}{dt} = -(k^*_s + k^*_{sc})\theta_s(t) + k^*_s\,\theta_g(t) + k^*_{sc}\,\theta_{sc} \qquad (8b)$$

where θ_h is again replaced by θ_m, usually $\tau_{d,h}$, S_v is considered to be constant, and the absence of an additional suffix for the parameters indicates that we are dealing with realistic physical parameters.

From eqns.(8) transfer functions can be derived. For example

$$H_{g,h} \triangleq \frac{\theta_g(s)}{\theta_m(s)} = K_{g,h} \frac{e^{-\tau_{d,h}s}(\tau_{s+1})}{a\tau_g\tau_s s^2 + a(\tau_g+\tau_s)s+1} \qquad (9)$$

with $K_{g,h} = ak^*_h/k^*_{tot}$, $k^*_{tot} = k^*_v + k^*_r + k^*_h + k^*$,
$a=(k^*_{tot}(k^*_s+k^*_{sc}))/(k^*_{tot}(k^*_s+k^*_{sc})-k^{*2}_s)$, $\tau_g=C_s/(k^*_s+k^*_{sc})$. For more details is referred to Udink ten Cate (1985b).

5. Results

The eqns.(8) are used for simulation and parameter estimation. Typical estimation results are given in table 3.

	Night	Day	
θ_{sc}	21.2 ^{0}C	22.0	
$C^*_g/60$	449.2	449.8	divided by 60 to yield
$C^*_s/60$	330	330	τ_g, τ_s in minutes
$k^*_r + k^*_v$	8.9	8.3	$k_v \simeq 0.5 - 0.8$
k^*_h	4.4	3.9	
	-	0.43	
k^*_s	6.4	4.8	
k^*_{sc}	3.0	1.1	

Table 3. Results of data fit for Naaldwijk glasshouse

Note that θ_{sc} is estimated. The values of k^*_h are in accordance with the values found in von Zabeltitz (1978, p. 166, table 42), which also holds for k^*_r. It is seen that differences between night and day are mainly represented in k^*_s and k^*_{sc}. It is not clear if this is due to the corridors in the glasshouse or to other phenomena.

Results for a night situation are shown in fig. 1a, and fig. 1b gives the high frequency signal components which are of most importance in control applications. To give a comparison the result of a combined model (eqn.6) is also depicted (fig. 1c) indicating that good results can be obtained when the soil temperature dynamics are neglected.

6. Conclusions

In this paper GCFC models have been presented which adequately describe the high frequency perturbations - which are of interest to control - as well as the low frequency working point. It is established that the soil energy storage is of much importance for the dynamic behaviour of greenhouses, an observation which is not earlier reported in the literature.

The parameters of the "general" GCFC model (which is not general when compared with the detailed physical models, e.g. Bot, 1983) are seen to conform with heating-load coefficients which are widely known in the literature (von Zabeltitz, 1978). The new model offers a solid base for future GCFC developments. Presently the model is applied in the development of a simulation system (Udink ten Cate, 1985c).

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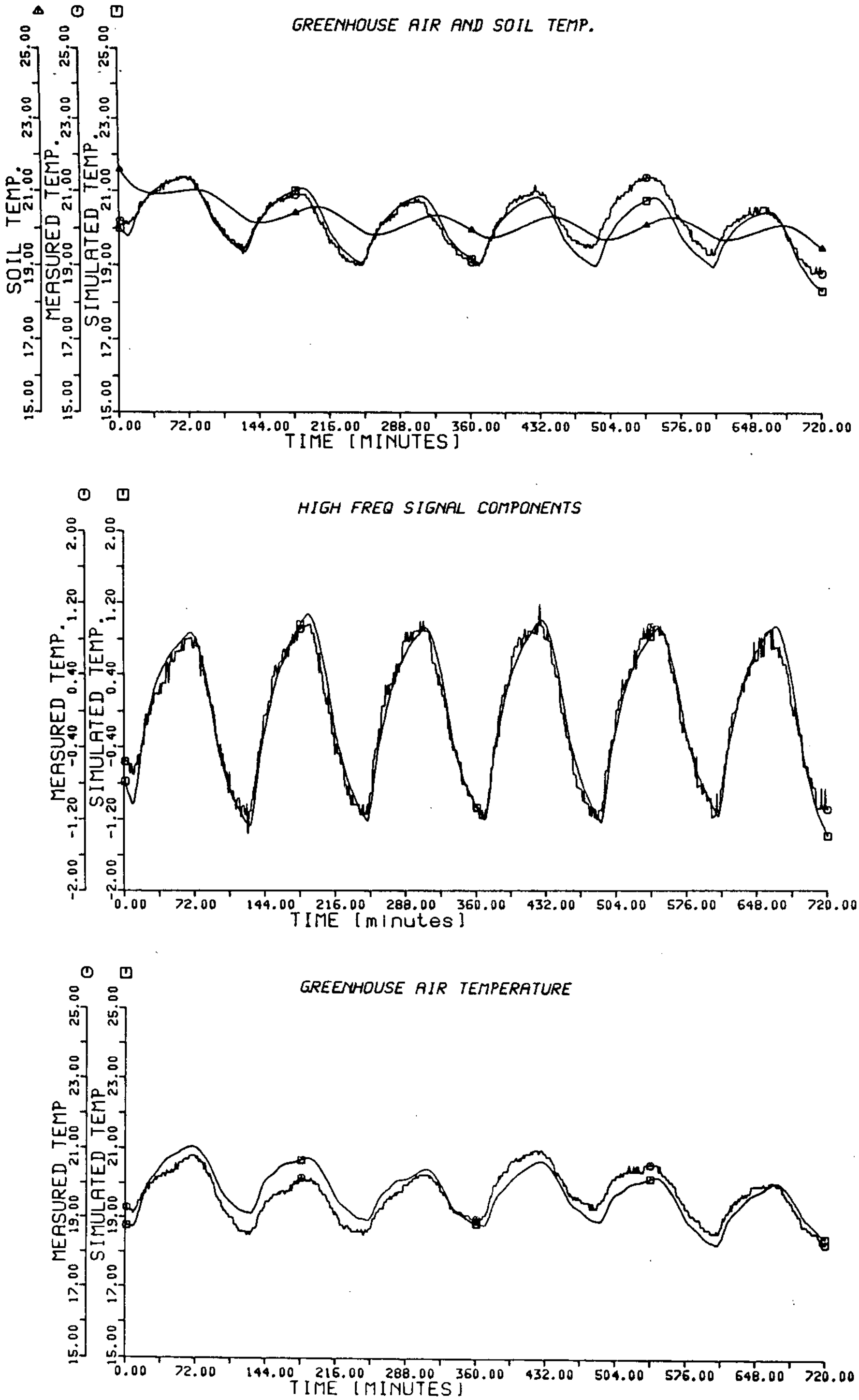

Fig. 1. Performance of the general model (a,b) and the combined model (c) in a test situation at night