A Model for the Climate of an Innovative Closed Greenhouse for Model Based Control

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Keywords: control, calibration, climate management, closed greenhouse

Abstract

A new greenhouse type is designed to study ways of decreasing horticultural water use in semi-arid regions. To control the greenhouse a model based control design will be applied. Hereto a model is needed to predict the systems behavior (1 day ahead), without much computational effort. A *physics-based model* for this new type of greenhouse is developed, based on enthalpy and mass balances. The greenhouse is divided in four compartments; the plant area, the roof area, the heat exchanger and the soil. For all compartments only the *main* energy and mass fluxes are modeled, in order to keep the model simple. Since the model describes only the main characteristics of the system with physical equations, careful calibration and validation (*systems identification*) is needed. Real data gained from the experimental greenhouse are used in a controlled random search to find the optimal parameter values.

INTRODUCTION

Water use efficiency is of prominent importance in regions where fresh water is scarce. In agriculture water use efficiency can be enhanced by introducing new ways of growing crops. The Watergy project (see www.watergy.info) studies possibilities of combining plant production with water recycling, space cooling and desalination in an experimental greenhouse (build in Almeria, Southern Spain).

Functioning of the Greenhouse

The most remarkable feature of the experimental greenhouse is the double walled tower (see Fig. 1). The sun heats the (humid) air inside (a), which rises into the outer duct of the tower (b) where it is further heated by the sun (c). The tower is closed at the top, so the air does not leave the greenhouse. Instead the air is cooled with a heat exchanger in the central duct of the tower (d). The cooled air falls and flows back into the warm greenhouse (e), closing the cycle. During night, the heat exchanger heats the air and the air movement reverses (hot air raises through the heat exchanger to the top of the tower and falls down through the outer duct).

Since the air cycle in the greenhouse is closed, the water evaporated by the plants stays inside. During day, warm, moist air flows into the tower, where the moisture condenses against the cold surface of the heat exchanger. To facilitate salt water desalination, a so-called inner roof (f) is used over which (salt) water is sprayed. This water evaporates on the inner-roof surface and condensates in the heat exchanger. For more information see Buchholz and Zaragoza (2004) and www.watergy.info for a general description and Janssen et al. (2005) for a description of the control system.

Specifications for the Model

Our ultimate goal is to control the greenhouse with a (adaptive) model predictive controller (MPC). In a MPC context a model is used to calculate the optimal future control actions. This method is also known as “optimal control”. The reason to choose for a MPC controller is the systems’ complex behavior. There are many restrictions in the inputs and multiple goals that (can) contradict. A MPC controller can take these restrictions into account and calculate the best settings for the actuators. Since a model

Proc. IIIrd IS on HORTIMODEL2006
Eds. L.F.M. Marcelis et al.
Acta Hort. 718, ISHS 2006

predictive controller needs to predict the effect of future control actions with the use of a model, it is computationally intensive. For this reason we have chosen to develop a model with a limited number of states.

MODEL

Many greenhouse models have been made in the past by various authors. One of the first to describe the greenhouse climate using physics-based models was Bot (1983). Later others followed, see for example Zwart (1996) and Tchamitchian et al. (1992). In his dissertation Tap describes a simple, physics based model that can be used in an optimal control setting (Tap, 2000). A similar type of model is needed for the Watergy greenhouse.

The greenhouse is divided into 4 compartments, namely the plant area (1), the inner roof area (2), the heat exchanger (3) and the soil (4) (see Fig. 1). In the first three compartments, the air enthalpy and moisture content are described by differential equations. For the soil, only the temperature is simulated. The heating exchanger is described with a four compartment model. The water input for the heat exchanger is the measured temperature in the real system.

Compartment 1: Plant Area

1. Enthalpy Balance of the Plant Area. The enthalpy balance of the plant area incorporates the main energy flows in the greenhouse, i.e. solar radiation, convection and conduction. We choose to add the energy input due to solar radiation energy directly to the greenhouse air, as suggested by Tap (2000). Heat losses due to convection and conduction are modeled in the standard way (Gaskell, 1992). The plant and the soil (evapo-)transpiration are not visible in the balance, since these processes transfer sensible heat into latent heat (both forms of energy are accounted for in the enthalpy). The energy released due to condensation of water on the greenhouse outer roof is assumed to be transferred outside.

The enthalpy balance is given by (see the appendix for the notation of the parameters):

rate of change of energy = solar radiation + convection + heat transfer from outside + …
heat transfer from soil + heat transfer to comp.2 – condensation on roof

$$m_1 \frac{dh_1}{dt} = \eta_1 G_0 A_{14} + \phi_a \left(h_3 - h_1\right) + U_{1o} A_{1o} \left(T_o - T_1\right) + U_{14} A_{14} \left(T_4 - T_1\right) + U_{12} A_{12} \left(T_2 - T_1\right) \qquad (1)$$
$$- r\, k_{1o} A_{1o} \left(\rho_{a,1} x_1 - \rho_{a,r} x_r\right)$$

2. Moisture Balance of the Plant Area. Moisture inside the greenhouse is transferred by convection, condensation and plant evapotranspiration. To calculate the amount of condensate on the roof, the roof temperature must be known. Since we want to limit the number of states, it was decided not to include the roof temperature as a state in the model. Instead, the temperature is estimated based on the heat transfer coefficients of the roof (see appendix).

Plant evapotranspiration can be modeled in various ways. The most well-known model for plant evapotranspiration is Penmann-Monteith (Monteith and Unsworth, 1990). These types of models make use of crop-specific-regression parameters. Stanghellini (1987) developed a plant transpiration model that is based on physics. However, also this model uses plant specific parameters (boundary (r_b) and stomatal (r_s) resistances). These parameters are estimated for most important crops in horticulture, see for example Bakker (1983) and Stanghellini (1987). The crop present inside the greenhouse at the time of the experiments was okra. Measurements of the stomatal resistance of Okra are sparse; the only available source are measurements by Ashraf et al. (2002). With two different cultivars they found stomatal conductances around 300 mmol/m^{2}s, which can be converted to 80 s/m (Tuzet et al., 2003). This is lower than literature values for C3 production crops, which have resistances of 100-200 [s/m] (Bakker, 1983; Stanghellini, 1987). The boundary layer resistance for okra can be estimated by choosing a canopy with corresponding shape. We choose for a boundary resistance between tomato and sweet pepper of 250 s/m. The total moisture balance of the plant area is described by the following function:

rate of change of moisture content = convection + plant transpiration – condensation on roof

$$m_1\frac{dx_1}{dt}=\phi_a\left(x_3-x_1\right)+E-k_{1o}A_{1o}\left(\rho_{a,1}x_1-\rho_{a,r}x_r\right) \tag{2}$$

where: $$E=\left(\frac{(2LAI)}{((1+\varepsilon)r_b+r_s)}\right)\left(\frac{x_{v,air}\varepsilon\left(r_b/2LAI\right)\eta_3 G_0}{r}-x_{v,air}\right) \tag{3}$$

(note that η3 is a correction term for the amount of solar radiation that is used by the plants)

Compartment 2: Inner Roof Area

The enthalpy and moisture balances of compartment 2 are similar to compartment 1, apart from the plants and the soil. Until now, spraying of (salt) water on the inner roof is not taken into account.

1. Enthalpy Balance of the Inner Roof Area.

rate of change of energy = solar radiation + convection + conduction from outside + ...
conduction to comp.1 – condensation on roof

$$m_2\frac{dh2}{dt}=\eta_2 G_0 A_{14}+\phi_a\left(h_1-h_2\right)+U_{2o}A_{2o}\left(T_o-T_2\right)+U_{12}A_{12}\left(T_1-T_2\right) \tag{4}$$
$$-r\,k_{2o}A_{2o}\left(\rho_{a,2}x_2-\rho_{a,r}x_r\right)$$

2. Moisture Balance of the Inner Roof Area.

rate of change of moisture content = convection + plant transpiration – condensation on roof

$$m_2\frac{dx_2}{dt}=\phi_a\left(x_1-x_2\right)-k_{2o}A_{2o}\left(\rho_{a,2}x_2-\rho_{a,r}x_r\right) \tag{5}$$

Compartment 3: Heat Exchanger

To model the heat and moisture transfer in the heat exchanger accurately, a spatially distributed model is needed. The heat exchanger is divided into four compartments, connected together. The condensation in the heat exchanger is calculated in the same way as the condensation on the greenhouse roof (see appendix). The heat of condensation is assumed to be transferred to the water in the heat exchanger. The temperature of the wall of the capillaries in the heat exchanger is assumed to be equal to the water temperature.

1. Enthalpy Balance of the Air in the Heat Exchanger.

rate of change of energy = convection in-out – conduction to water in heat exchanger -
condensation on capillaries in the heat exchanger

$$m_{a,i}\frac{dh_{3,i}}{dt}=\phi_a\left(h_{3,i-1}-h_{3,i}\right)-U_{hex}A_{hex,i}\left(T_{a,i}-T_{w,i}\right)-r\,k_{as}A_{hex,i}\left(\rho_{a,i}x_{a,i}-\rho_{a,surf}x_{surf,i}\right) \tag{6}$$

For i=1: $h_{i-1}=h_{in}$

2. Moisture Balance of the Air in the Heat Exchanger.

rate of change of moisture content = convection in-out – condensation on the heat exchanger
surface

$$m_{a,i}\frac{dx_{3,i}}{dt}=\phi_a\left(x_{3,i-1}-x_{3,i}\right)-k_{as}A_{hex,i}\left(\rho_{a,i}x_{a,i}-\rho_{a,surf}x_{surf,i}\right) \tag{7}$$

For i=1: $x_{i-1}=x_{in}$

3. Heat Balance of the Water. The heat transport by the water is given by:

rate of change of energy = convection in-out + conduction to water in heat exchanger

$$m_{w,i} Cp_w \frac{dT_{w,i}}{dt} = \phi_w Cp_w \left(T_{w,i+1} - T_{w,i}\right) + U_{hex} A_{hex,i} \left(T_{a,i} - T_{w,i}\right) + r\, k_{as} A_{hex,i} \left(\rho_{a,i} x_{a,i} - \rho_{a,surf} x_{surf,i}\right) \quad (8)$$

For i=4: $T_{w,\ i+1} = T_{water,in}$

Compartment 4: Soil

The soil is assumed to be one layer, with capacity Cp_{soil} [J/kgK]. This layer exchanges heat with both the plant area air (convection) and the deep soil (conduction). Radiation is not taken into account, since it has a second order effect in comparison to the other forms of energy transfer (the solar radiation is added directly to the greenhouse air).

rate of change of energy = convection from compartment 1 – conduction to deep soil

$$m_4 Cp_s \frac{dT_4}{dt} = U_{14} A_{14} \left(T_1 - T_4\right) - U_{ds} A_{14} \left(T_{ds} - T_4\right) \quad (9)$$

Implementation

The model was implemented in Matlab and simulated using the build-in ordinary differential equation solver (ODE45). This ODE solver uses a varying step size, depending on the smoothness of the function (or model) at each time instant t.

RESULTS

Model Calibration

All the parameters in the model have a physical meaning and most of them can be given values from the literature. A crucial parameter for the functioning of the heat exchanger is the heat transfer coefficient (U_{tot} [W/m^{2}K]). To make a good estimate for this parameter, steady state experiments with the heat exchanger have been performed. From these measurements, the heat transfer coefficient was determined to be 30 W/m^{2}K.

The airflow through the greenhouse is a key variable in the model. The air velocity is a function of the pressure difference in the tower (caused by the temperature difference between top and bottom and the ventilator). From measurements it was found that the airflow is almost constant during the whole day (when the fan is on and the heat exchanger is cooling the air). In the model the airflow is assumed to be constant (0.5 m s^{-1} = 2.5 kg s^{-1}).

The parameters of the plant model are taken from literature (the boundary resistance is 250 s/m, the stomatal resistances is assumed to be 80 s/m).

Controlled Random Search

The three parameters in the model that account for the fractions of solar radiation that are used in compartments 1, 2 and the plant (η_1, η_2 and η_3) could not be taken from the literature, nor could they be estimated in a small experiment. Estimates for these parameters were produced with the controlled random search algorithm (CRS). Basically, this method randomly chooses values for the parameters to be estimated, runs the model with these parameters and calculates a goal function (usually the sum of the squared errors). By trying to improve the result of this goal function, the parameter values converge to an optimum. The CRS minimizes the risk of local minima because the method scans through the whole parameter space. A disadvantage is the longer calculation time that is required. See Price (1976) for a detailed description of the CRS-algorithm.

The results of one of the runs with the CRS are shown in Fig. 2. The left graph shows the values for η_1, η_2 and η_3 that were evaluated during the simulations (upper three graphs), the lowest graph shows the goal function (the sum of the squared errors between the simulated model and the measured values). The right graph shows the distribution of the estimated parameter values. The estimate for η_1 and η_2 is quite good, since the distribution of the estimated values is low. The estimate for η_3 has a much wider distribution, making the estimated value less certain.

Model Validation

After the calibration of the model with the methods described above, the model was validated with an independent, typical dataset (Fig. 3). The shape of the graphs for the simulated and measured data is almost the same. This indicates that the model structure is well chosen. If the shape of both curves is different, it is possible that important dynamic behavior of the greenhouse is not taken into account in the model. The results for the simulated temperature values are shown in Fig. 3.

The temperature deviation is relatively small. There is a small underestimation of the temperature at the beginning and at the end of the day. The model for moisture content in the inner roof compartment is as good as the temperature model (not shown in the graph); the moisture content is underestimated by about 2 g/kg (approximately 8%). One of the reasons for this could be the estimates for the plant-specific parameters in the plant model (boundary and stomatal resistance).

Performance

The time to simulate one day with the model is in the order of one minute (in Matlab, using ODE45 and a P4-2.5GHz computer). For use in a model predictive controller, this is quite long, although the required speed of the model depends mostly on the interval at which the controller has to calculate a new series of setpoints. To improve the computational speed, it is possible to implement the model in a different programming language, for example C.

CONCLUSIONS

A model is developed that describes the dynamic behavior of the greenhouse with a limited number of states. The key-parameters of the model are identified with a controlled random search algorithm. The computational time is at the moment considerably long (using Matlab), but can be improved using a different programming language for the implementation (e.g. C-code). When the calculation time is shortened, the model is suitable for use in a model predictive controller. To account for changes in the model parameters (for example seasonal changes) the model predictive controller can be enhanced by making it adaptive.

The plant model is quite complicated when compared to the model of the greenhouse climate. The number of parameters in the plant model is large and the parameters are difficult to estimate independently from each other. For future research, it would be good to look for a less complicated plant model that can describe plant evapo-transpiration accurately.

In conclusion we can say that a simple compartment model for an experimental, closed greenhouse is derived that can mimic the real systems behavior satisfactory. By identifying only the key-parameters in the model, it was possible to keep the calibration of the model simple but accurate. The validated model is suitable for use in a model based control strategy for the greenhouse control.

ACKNOWLEDGEMENTS

This research was funded by the European Union under contract number NNE5/2001/683.

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APPENDIX 1: ADDITIONAL FUNCTIONS

Estimation of Surface Temperature of the Capillaries

The surface temperature is estimated based on the given heat transfer coefficient (λ [W/mK]) on the heat exchanger and the measured total heat transfer coefficient (U_{tot} [W/m^{2}K]). The capillaries separate the water from the air. To calculate the amount of condensation on the capillaries, the surface temperature must be calculated. This can be done in the following way:

The heat resistances of the heat exchanger are known:

$$R_{tot} = 1/U_{tot} = 1/\alpha_{as} + d_s/\lambda_s = 1/\alpha_{ws} \tag{10}$$

Compared to α_{as}, α_{ws} can be neglected. This results in the following formula for α_{as}:

$$R_{as} = 1/\alpha_{as} = 1/U_{tot} - d_s/\lambda_s \text{ [m}^2\text{K/W]} \tag{11}$$

The temperature of the capillaries can be estimated with:

$$\begin{aligned} &Q_{tot} = (T_a - T_w)/R_{tot} \\ &\Rightarrow T_s = T_a \pm R_{as}/R_{tot}(T_a - T_w) \quad \{\text{if Ta} > \text{Tw} : \text{-}, \text{else} +\} \end{aligned} \quad \text{[W/m}^2\text{]} \tag{12}$$

APPENDIX 2: NOTATIONS

parameter		parameter	
δ	slope of saturation function curve [Pa/K]	mol_{H20}	molecular mass water [kg/mol]
ε	δ/γ [-]	p	vapor pressure [Pa]
η	radiation efficiency factor [-]	Pair	mean air pressure [Pa]
γ	psychometric constant [Pa/K]	phi	mass flow [kg/s]
λ	heat conduction coefficient [W/m^{2}K]	r	heat of evaporation [kJ/kg$_{(water)}$]
ρ	air density [kg/m^3]	R	universal gas constant [J/mol m^3]
σ	Boltzmann constant [W/m^{2}K^4]	r_b	boundary resistance of the canopy [s/m]
Cp_{da}	specific heat dry air [kJ/kg.K]	R_{net}	nett radiation [W/m^2]
d_s	thickness of the capillary wall [m]	r_s	stomatal resistance of leaves [s/m]
E	plant transpiration rate [kg/m^{2}s]	svp	saturated vapor pressure [Pa]
G_o	solar radiation rate [W/m^2]	T	temperature [°C]
h	enthalpy [J/kgK]	U_d	heat transfer to deep soil [W/m^{2}K]
k	mass transfer coefficient [m/s]	U_{tot}	total heat transfer coefficient [W/m^{2}K]
k_l	extinction coefficient for long wave radiation [-]	x	moisture content [kg$_{(moisture)}$/kg$_{(air)}$]
k_s	extinction coefficient for shortwave radiation [-]	x_a^*	saturated moisture content of the air [kg/kg]
LAI	leaf area index [m$^2_{(leaf)}$/m$^2_{(soil)}$]	x_s	saturated moisture content [kg$_{(moisture)}$/kg$_{(air)}$]
Le	Lewis number = a/ID = λ/(ρ Cp) [-]	x_{surf}	saturated moisture content of the air at the surface temperature [kg$_{(moisture)}$/kg$_{(air)}$]
m	mass [kg]	x_v	moisture concentration [kg$_{(moisture)}$/kg$_{(air)}$]
mol_{air}	molecular mass air [kg/mol]		

Subscripts

a	air	*hex$_{out}$*	heat exchanger out	*r*	roof
c	cover	*i*	inside	*tot*	total
c1	compartment 1	*ij*	from comp. i to comp. j	*w*	water
da	dry air	*l*	leaf		
ds	deep soil	*o*	outside		

Figures

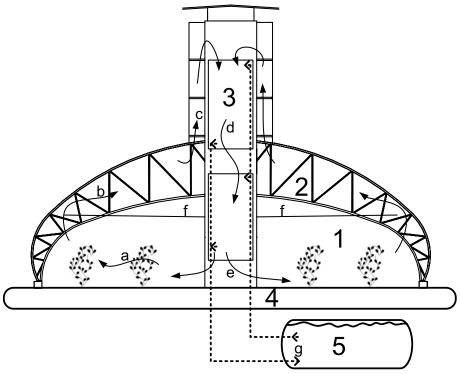

Fig. 1. The Watergy greenhouse at day-time.

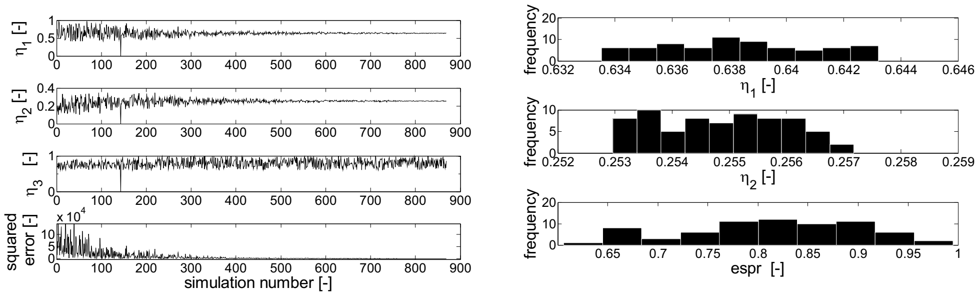

Fig. 2. Results of the controlled random search algorithm. Left: evaluated parameter values and the goal function, right: distribution of the parameter values.

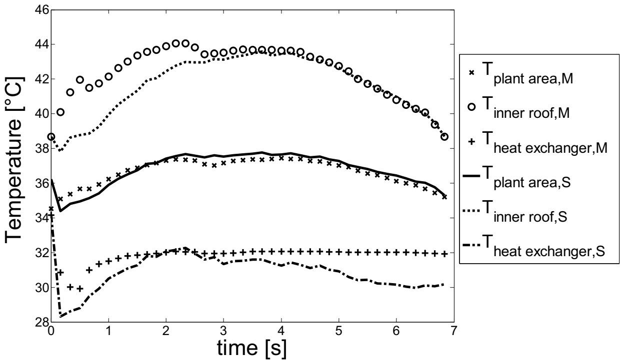

Fig. 3. Simulated (S) and Measured (M) temperature in the greenhouse.