A Real-Time Energy Balance Model of a Large Scale Greenhouse

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Abstract

A greenhouse is a controlled environment. Climate parameters like temperature and humidity are controlled by venting, heating and cooling. Shading light and dosing CO_2 influence other growing conditions like light level and CO_2-concentration. In a dry and hot climate like Arizona forced ventilation with evaporative cooling is used to maintain favorable growing conditions.

Forced ventilation means full control over the amount of air exchanges. Together with known ambient conditions like temperature, relative humidity and incoming solar irradiation, all input data are available to model the energy flows in a greenhouse.

The steady state balance between the energy input from the sun and the forced cold air is calculated and the result is shown as a temperature and relative humidity. The 'cooling capacity' of the crop on the greenhouse climate is part of the model. Characteristics of the greenhouse cover and the evaporative cooling can be adjusted.

This model is presented in a user-friendly interface. It is realistically shown as a cross-section of a greenhouse with all relevant parameters visible, both input variables like ambient conditions and the resulting calculated values of the greenhouse climate such as temperature and humidity. The model calculates the greenhouse temperature and humidity under steady-state conditions. The model can be used as a learning tool for growers. All relevant ambient conditions can be used as input data to calculate the greenhouse climate.

The model is validated using real data recorded on sunny days in May 2008.

INTRODUCTION

Growers in commercial greenhouses are using computer controlled climate systems to maintain the right growing conditions in the greenhouses. In general, climate conditions are temperature, humidity, light and CO_2. In a traditional greenhouse these parameters can be influenced through heating, venting, shading and CO_2-dosing.

Air exchanges have a major effect on temperature, humidity and CO_2-levels. To calculate the ventilation rate in a traditional greenhouse without forced cooling some algorithms have been developed based on vent opening (size and shape), temperatures, wind speed and wind direction. The results of these calculations are just indicative and cannot be used for an accurate energy balance calculation. In a warm dry climate like South-west Arizona another tool, i.e., evaporative cooling is used to control the temperature and humidity in the greenhouses.

Changing one parameter will affect others, e.g., more venting to reduce the greenhouse temperature will change the humidity level and CO_2-concentration.

At Eurofresh greenhouses (Wilcox, AZ, U.S.A.) all greenhouses have evaporative cooling to be able to grow during the summer months. An experimental greenhouse has been built with forced ventilation to get even better control over the air exchange rate and the greenhouse climate. This greenhouse has all hardware and software available to be used as a research tool for making a reliable energy balance during cooling and heating periods.

The aim of this study was to determine climatic conditions inside the greenhouse based on actual ambient climate conditions and characteristics of the climate control settings, e.g., ventilation rate, shading, Pad&Fan cooling. It may be used as a research tool, i.e., modeling a greenhouse which calculates the actual conditions as good as possible. Model predictions are compared with actual measurements.

MATERIALS AND METHODS

The experimental greenhouse model is shown realistically in Figure 1. This greenhouse is a fully controlled environment. Modulating fans and vents at the outside gable of the greenhouse control the amount of air entering the greenhouse. Roof vents are only used to release air from the greenhouse to ambient. Air can be fully or partly recirculated through the greenhouse by adjusting a second air valve in the greenhouse. The relation between fan speed and airflow through the gable openings has been measured when there is no internal recirculation.

The incoming energy is the solar irradiation in W m^{-2} or J s^{-1} m^{-2}. The ambient irradiation is measured together with the transmittance (%) of the greenhouse cover. The greenhouse area is measured in m^2.

The total energy flux to the greenhouse is:

$$\text{Energy flux (J s}^{-1}) = \text{Irradiation (J s}^{-1}\text{ m}^{-2}) * \text{transmittance (\%)} * \text{greenhouse area (m}^2)$$

The ventilation rate or mass flow (kg s^{-1}) is set by the fan capacity. The conditions of the incoming air (ambient) are known (air temperature and relative/absolute humidity). The pad wall will lower the air temperature and increase its relative and absolute humidity but since no energy is added or taken from the incoming air by the pad wall, the enthalpy of the air leaving the pad wall will remain the same.

The enthalpy of the incoming air is calculated. Air at 0°C is defined to have an enthalpy of 0 kJ kg^{-1}. The enthalpy, in kJ kg^{-1}, at any temperature, t, between 0 and 60°C is approximately:

$$h = 1.007t - 0.026 \quad (1)$$

The enthalpy of liquid water is also defined as 0 kJ kg^{-1} at 0°C. To turn liquid water to vapor at the same temperature requires 2501 kJ kg^{-1} at 0°C. At temperature t the heat content of water vapor is:

$$h_w = 2501 + 1.84t \quad (2)$$

The enthalpy of moist air, in kJ kg^{-1}, is therefore:

$$h = (1.007t - 0.026) + g * (2501 + 1.84t) \quad (3)$$

where, g is the water content in kg kg^{-1} of dry air.

The air in the greenhouse will rise in temperature and absolute humidity due to the heat load from the sun. The air exiting the greenhouse will have a rise of enthalpy of:

$$d(h) = \text{energy flux (kJ s}^{-1}) / \text{mass flow (kg s}^{-1}) = \text{kJ kg}^{-1} \quad (4)$$

The enthalpy of the air leaving the greenhouse is:

$$h_{air\ GH\ exit} = h_{air\ GH\ enter} + d(h) \quad (5)$$

All other energy flows, i.e. due to temperature differences between greenhouse air temperature and ambient are not calculated. Therefore the model is less sophisticated as other greenhouse models used for calculating energy balances.

Absolute air pressure has only a minor effect of the enthalpy of (moist) air. No shading or energy screen is used. A special whitewash, Reduheat, is applied on the outside of the roof to limit the amount of heat (Near Infrared Radiation, NIR) entering the greenhouse without limiting the amount of Photosynthetic Active Radiation (PAR) too much. The transparency of the roof cover is measured on a regular basis to check the wear and tear of the Reduheat due to wind, rain, and dust. Ambient climate conditions like temperature, humidity, and irradiation are monitored as well. Irradiation is measured with a Kipp&Zonen sensor (model CMP3, Delft, the Netherlands). Temperature and humidity is measured with an electronic measure box (E-box) from Priva (Priva, de Lier, the Netherlands). Data sampling is every minute, recorded as a 5 minute average in a Priva server climate control computer (Priva, de Lier, the Netherlands).

Interior climate parameters such as air temperature, relative humidity or vapor pressure deficit, and CO_2 concentration are constantly monitored. Data sampling is every minute, recorded as a 5-minute average in a Priva server climate control computer (Priva, de Lier, the Netherlands). These parameters are measured at different positions in the greenhouse, e.g., entering the air ducts, within the crop at the roots and the head and at the roof openings.

Heat is delivered through water-to-air heat exchangers and distributed through air ducts. Cooling is done through evaporative pads and distributed through the same air ducts. No additional humidity control like a misting system is used. CO_2 is supplied by burning natural gas in boilers, with heat storage for night heating, and distributed through small air hoses in the greenhouse.

Figure 1 shows the user interface of the model, i.e., a cross-section of the experimental greenhouse. All data in the square boxes and bold print can be changed; all data in underlined and bold print are calculated values. Input data are: ambient temperature (T_{amb}), and relative humidity (RH_{amb}), pad wall thickness (*thickness*), ventilation rate (*fan cap*), additional supply of CO_2 (*CO_2 supply*), irradiation, greenhouse cover transmittance (Tr_{GH}), reflectance of the crop (R_{crop}), energy flow to or from the soil (P_{soil}).

With this model, a user can easily change input data and check the results instantly. One may set current ambient conditions to see if the actual greenhouse temperature is calculated right. Data from May 26 and 27 (2008) have been used to validate the model.

The model shows greenhouse air temperature (T_{GH}) and relative humidity (RH_{GH}) of the air exiting the greenhouse. These are parameters known to growers. In this greenhouse model temperature or relative humidity can be set independently of the other. A desired humidity level can be set to calculate the temperature or a desired temperature can be set to calculate the relative humidity. In a steady state condition the enthalpy of any combination (within physical limits) of temperature and relative humidity is the same. Selecting a higher temperature will calculate a lower relative humidity to get the right enthalpy. Selecting a higher relative humidity will calculate a lower temperature. To compare the calculated data with the measurements, the enthalpy of the air is used. This makes the validation of the model easier. The measurement of the enthalpy of the air is based on measurements of dry bulb temperature and relative humidity at 4 positions at the top of the greenhouse. Any other energy flux is neglected, e.g., conductivity through the closed roof cover due to differences in temperature, reflectance of the crop and dynamic effects like heating up of the soil and crop.

A similar model is made for a '*traditional*' *Pad&Fan greenhouse* (Fig. 2). The setting of 'cooling capacity' of the crop, i.e., transferring sensible heat into latent heat by evaporating water can be changed. Increasing the cooling capacity of the crop means transferring more incoming energy into latent heat. This will reduce the dry bulb temperature but will increase the relative humidity. A dense canopy gives more cooling capacity than a young crop cover. Additional measurements of temperature and humidity in the greenhouse are required to validate the model for a traditional Pad&Fan greenhouse.

RESULTS AND DISCUSSION

The Experimental Greenhouse

Some results are shown in Table 1 and 2. The measured and calculated value of the enthalpy of the exiting air is shown in the last 2 columns. The calculated values are lower than the measured values. There may be several reasons for this difference. An important one will be the transmittance of the greenhouse cover. It has been measured in the greenhouse but any construction like a steel column will reduce the internal light level but not the heat load. Any light absorbed by the internal construction parts in the greenhouse will be (partly) transferred to sensible heat and adding to a rise in temperature and enthalpy of the greenhouse air. A roof support reduces the amount of light available for the crop but does not reduce the internal heat load equally. The measurement of the light transmittance of the cover material and internal construction overestimates the actual reduction of the heat load of the internal construction. So measured temperatures will be higher than calculated temperatures.

The agreement between the calculated and measured data is sufficient to use the model as a training tool for growers. The calculated greenhouse temperature and relative humidity give the grower confidence in the model to use it and to get familiar with the experimental greenhouse. By adjusting input data like ambient conditions or ventilation rate the model shows the change in climate conditions. To be able to use this model as a validated research tool to predict greenhouse climate conditions better algorithms should be used. Factors like light reflecting from the crop and energy storage and release from the soil may be added.

Traditional Pad&Fan Greenhouse

For a ‘traditional’ Pad&Fan greenhouse the user interface is seen as a powerful tool for inexperienced people to show the impact of adjustments on the greenhouse climate. With just a change of ambient conditions, the ventilation rate, or the crop cooling capacity one can easily see the changes in the greenhouse climate. No data are available yet to compare measurements with computed data.

The user interface is a strong tool to show growers and supervisors the impact of ambient conditions on the greenhouse climate. To improve the agreement between measured and calculated data, additional algorithms may be added. More measurements are needed to validate both models.

Literature Cited

Padfield, T. Equations describing the physical properties of moist air. http://www.padfield.org/tim/cfys/atmcalc/atmoclc2.pdf

<u>Nomenclature</u>

Parameters	Units	Parameters	Units
Transmittance	%	Temperature T	°C
Energy flux	J s^{-1}	Relative humidity RH	%
Enthalpy dry and moist air h	kJ kg^{-1}	Humidity deficiency HD	g kg^{-1}
Water content g	kg kg^{-1} of dry air	Reflectance if crop R_{crop}	%
Parameters used in figures		Ventilation rate VR	m^3 m^{-2} min^{-1}
Dew point T_{wb}	°C		
Enthalpy dry and moist air H	kJ kg^{-1}		
Transmission Tr GH	%		
Energy flux of soil P_{soil}	W m^{-2}		
Solar irradiation	W m^{-2}		
Greenhouse area	m^2		
Mass flow	kg s^{-1}		
Enthalpy water h_w	kJ kg^{-1}		

Tables

Table 1. Comparisons of model predictions with measured enthalpy values for May 28, 2008.

26-May-08	Ambient conditions			Measured	Calculated
	irradiation	T	RH	E air exit GH	
time	W/m2	°C	%	(kJ/kg)	(kJ/kg)
9:00 - 10:00	770	20.3	29	66.7	64.0
10:00 - 11:00	933	21.8	26	73.3	69.7
11:00 - 12:00	1034	22.8	23	77.9	70.3
12:00 - 13:00	1061	23.4	22	77.7	73.7
13:00 - 14:00	1033	24.6	19	84.6	78.2

Table 2. Comparisons of model predictions with measured enthalpy values for May 27, 2008.

27-May-08	Ambient conditions			Measured	Calculated
	irradiation	T	RH	E air exit GH	
time	W/m2	°C	%	(kJ/kg)	(kJ/kg)
9:00 - 10:00	744	21.3	30	65.2	63.6
10:00 - 11:00	912	23.4	24	74.6	67.6
11:00 - 12:00	1022	25.2	22	74.7	70.2
12:00 - 13:00	1046	26.5	20	75.8	72.0
13:00 - 14:00	1025	27.9	19	78.4	73.8
14:00 - 15:00	938	28.8	16	80.9	70.9

Results from 2 sunny days in May 2008 for the experimental greenhouse. Data are used for a time period with only cooling and no recirculation of air from the greenhouse through the pad wall.

Figures

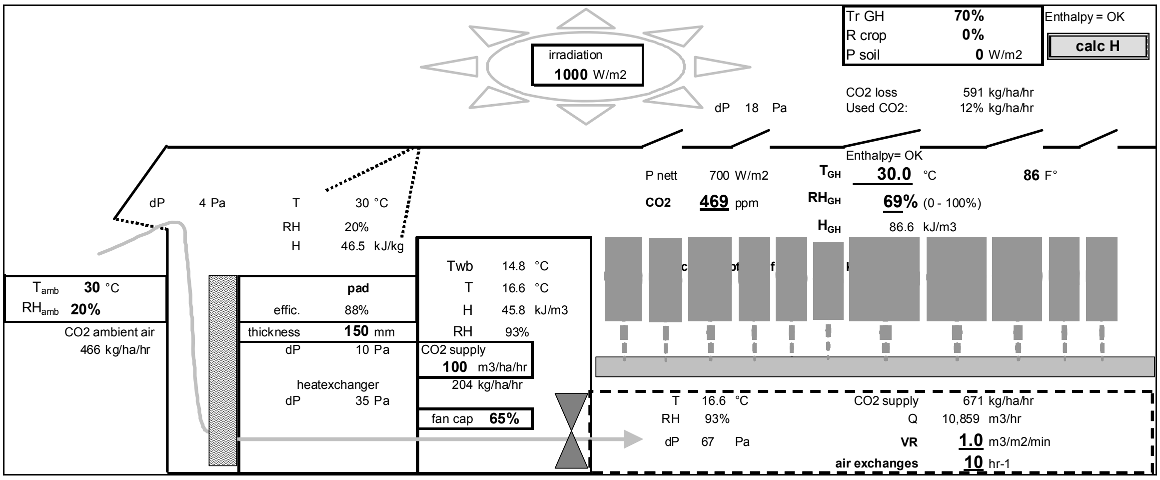

Fig. 1. Experimental greenhouse cross section. Cross section of the experimental greenhouse and user interface.

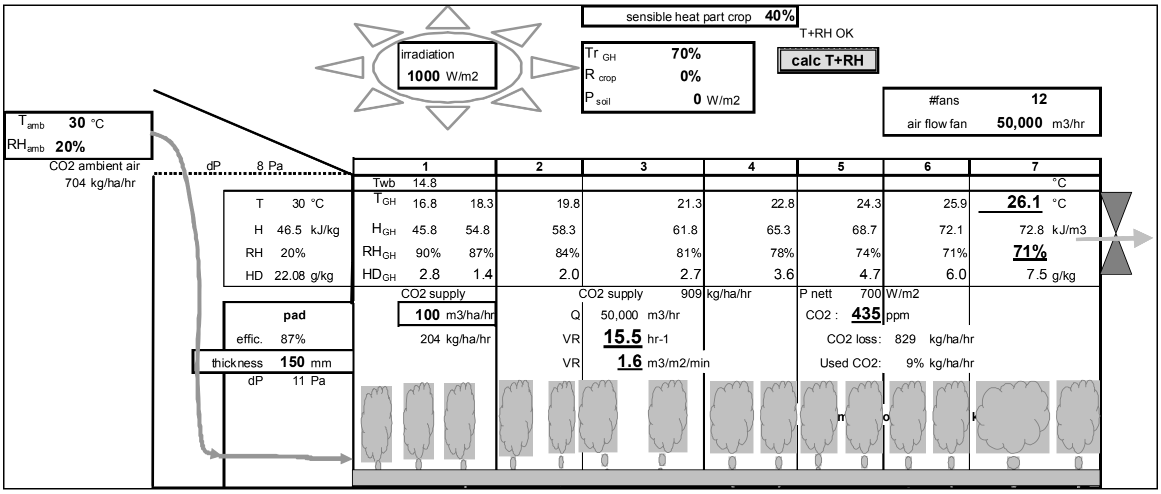

Fig. 2. Traditional Pad& Fan greenhouse cross-section. A cross-section of a 'traditional' Pad&Fan greenhouse is shown as 7 bays where temperature and humidity is calculated. In section 4 the actual greenhouse temperature and humidity is measured to control the greenhouse climate. Air is moving from left to right through the greenhouse. The temperature goes up and relative humidity goes down.