Measured energy use in a greenhouse with tomatoes compared to predicted use by a mechanistic model including transpiration

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Abstract: In regions with a colder climate the use of heat energy for climatization of greenhouses can be significant. Beside outdoor temperatures and climate also transpiration affects the use of heat energy since heating and ventilation or dehumidification may be required in order to keep the humidity in the greenhouse below levels which may lead to plant diseases. A reliable model is a powerful tool to predict energy use for greenhouse cultivation. Thus, a mechanistic model including transpiration and energy use for dehumidification and hourly output data was developed from an older simpler model. To be reliable, modelled data must fit with real data. The aim of the present study is to compare measured and modelled use of heat energy. Thus, energy use for a greenhouse with tomatoes was measured and compared to modelled data. The greenhouse in the study is of Venlo-type and the floor area is 80 000 m2. The cover material is single glass and screens are used in order to provide extra insulation during night time. The heating system is water based with heating pipes. Heat energy use was calculated from temperatures of incoming and outgoing heating water and pulses from two flow meters. Climate parameters and screening positions were registered and stored by the help of a Priva system. The model includes solar radiation according to equations provided by Duffie and Beckman (1974), and transpiration equations provided by Stranghellini (1987). Solar radiation is in the model divided into diffuse and direct insolation. Ventilation rate is calculated from moisture balance. Properties of the greenhouse in question, i.e. its material properties, areas, etc. are in combination with climate parameters and screening input data for the model. Measurement of heat energy use and climate was made on hourly basis during a period from April to September. Daily average climate values during the months April to September ranged for the separate months from 10-19 MJ/d for outdoor incoming solar radiation, 8.2℃-17.2℃ for outdoor temperature, 18.3℃-20.3℃ for indoor temperature, and 80%-84% for indoor RH. Monthly values for measured use of heat energy per m2 greenhouse area for the months April, June, July, August and September were 157, 130, 74, 94, 108 and 121 MJ/month/m2 respectively. Modelled amounts of energy for the same months were 159, 125, 61, 69, 73 and 110 MJ/month/m2. A regression between measured and modelled daily use of heat energy for the whole period between April and September showed a fairly good agreement (R2 = 0.75). Data indicate that heat storage in the heating system increase the energy use. Further, the data suggest that also heat storage in mass inside the greenhouse should be included in a model predicting heat energy use in greenhouses.

Keywords: greenhouses, energy, measurements, modelling

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1 Introduction

In regions with a colder climate the use of heat energy for climatization of greenhouses can be significant. For greenhouse growers this means higher production costs. Further, energy consumption also leads to increased emissions of greenhouse gases in most cases.

In food production, we gain energy and nutrients in products to be consumed, but in order to do that there are also energy expenditures involved and in order to prevent increased greenhouse gas emissions from the agricultural sector it has been argued that both the global consumption of animal products like meat and the intensity of greenhouse gas emissions from the livestock

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production must be decreased (McMichael et al., 2007). Also the intensive production of greenhouse crops leads to greenhouse gas emissions and emissions related to heat energy use can be large. Recent years an increased interest in ways to limit greenhouse gas emissions from agricultural production has led to a number of studies of the carbon footprint of various food productions and also the carbon footprint of tomato production has been studied by e.g. Page et al. (2012).

Beside outdoor temperatures and climate also transpiration affects the use of heat energy in greenhouses since heating and ventilation or dehumidification may be required in order to keep the humidity in the greenhouses below levels which may lead to plant diseases.

In greenhouses at northern latitudes growers have to dehumidify which leads to an increase in energy use (de Halleux and Gauthier, 1998). Dehumidification in the greenhouses is needed in order to lower the risk for fungal diseases and in order to prevent physiological disorders (Campen et al., 2009).

In Sweden a development towards renewable energy use in greenhouse production has accelerated latest years with much use of biofuels which now represents a lot of the fuel used for greenhouse heating (SJV, 2012). Anyhow, there is a large interest in further development towards sustainability and in decreasing the amount of heat energy used in the greenhouses.

Although efforts have been done to quantify the humidification requirements for greenhouses which can be large and costly in cold climate there still seems to be a need for precise moisture balance models (Han et al., 2012).

A reliable model is a powerful tool to predict energy use for greenhouse cultivation. Such a tool can be used for analysing energy conservation for various design criteria and installations, e.g. for dehumidification. Thus, a mechanistic model including transpiration and energy use for dehumidification and hourly output data is being developed from an older simpler model. To be reliable, modelled data must fit with real data.

1.1 Aim of the study

The aim of the present study was to compare measured and modelled use of heat energy. Thus, the heat energy use for a greenhouse with tomatoes was measured and compared to modelled data. The ultimate aim is to develop a precise model for prediction of energy use in greenhouses.

2 Materials and methods

In the study measured heat energy use was compared with model predicted heat energy use in order to validate a software model being developed.

2.1 The greenhouse

The greenhouse in the study is of Venlo-type, and the floor area is 80 000 m^2. The greenhouse is rectangular shaped with eight compartments, the cover material for both walls and roof is single glass, and screens are used in the whole house in order provide extra insulation during night time. The glass sheets used are of the size 1.5 × 0.8 m each. The height to the gutter is 5.0 m and the lower parts of the walls are additionally insulated.

The heating system is water based with heating pipes and the fuel is natural gas. The heating system consists of two circuits, and inlet and outlet temperatures were on average about 82℃ and 37℃ respectively during the study. Heating pipes are located both below and above the plant canopy.

2.2 The measurements

Hourly data of indoor and outdoor climate as well as of heating were registered and used for evaluation. The climate in the greenhouse was registered by two or more temperature and humidity sensors in each compartment.

Heat energy use was calculated from temperatures of incoming and outgoing heating water measured by Pt100 sensors and pulses from two flow meters (Hydrometer WP-XKA model 457, nominal diameter 200 mm, pulse rate 250 pulses/litre).

Outdoor temperature and wind speed were registered by sensors of a Priva meteorological station placed on the roof of the greenhouse. Solar radiation was measured by Kipp & Zonen solarimeters mounted on the roof.

Climate parameters and screening positions etc. were registered and stored by the help of a Priva system except for the outdoor relative humidity which was collected from a nearby meteorological station.

The measurement of heat energy use and climate was made on hourly basis during a period from April to September.

2.2 The simulation model

The simulation model used for predicting the heat energy use in the greenhouse uses the Powersim software platform and it is being developed from an earlier model (EBBE) frequently being used in Sweden for energy calculations related to greenhouses. The model includes solar radiation according to equations provided by Duffie and Beckman (1974), and transpiration equations provided by Stanghellini (1987). Solar radiation is in the model divided into diffuse and direct insolation. The direction of the beam radiation is calculated from latitude and longitude of the greenhouse, date of the year, and time of the day. The share of solar radiation on a certain greenhouse surface entering the greenhouse is calculated from angle dependent reflection and transmission. Ventilation rate is calculated from moisture balance. Properties of the greenhouse in question, i.e. its cover material properties regarding heat transfer and light transmission, wall and roof areas, infiltration rate, orientation of surface areas, estimated LAI (leaf area index) etc. are in combination with hourly measured climate parameters (including solar radiation but not wind speed) and measured screening positions input data for the model.

2.2 Statistical evaluation

For evaluation of the model predictions of heat energy supply demands compared to measured heat energy supply and also for treatment of other data collected in the study, the statistical software package Minitab was used.

3 Results

Daily average climate values during the months April to September ranged for the separate months from 10-19 MJ/d for outdoor incoming solar radiation, 8.2℃-17.2℃ for outdoor temperature, 18.3℃-20.3℃ for indoor temperature, and 80%-84% for indoor relative humidity (RH) (Table 1). As can be seen, solar radiation was significantly lower for the month of September compared to the other months.

Table 1 Daily average values of solar radiation, wind speed, greenhouse and outdoor temperatures and relative humidity for different months of the experiment

Month	Solar radiation MJ/d	Wind speed m/s	Temp., outdoors ℃	RH, outdoors %	Temp., greenhouse ℃	RH, greenhouse %
April	17.4	3.95	8.2	69	19.4	82
May	18.4	3.34	11.6	73	19.9	84
June	19.0	3.41	16.2	72	19.9	82
July	16.9	3.83	16.0	78	19.7	82
Aug	15.5	3.76	17.2	78	20.3	80
Sept	9.9	4.33	13.0	81	18.3	81

Monthly values for measured and modelled use of heat energy per m^2 greenhouse area are shown in Figure 1. The measured values for the months April, June, July, August and September were 157, 130, 74, 94, 108 and 121 MJ/month/m^2 respectively. Modelled amounts of energy for the same months were 159, 125, 61, 69, 73 and 110 MJ/month/m^2.

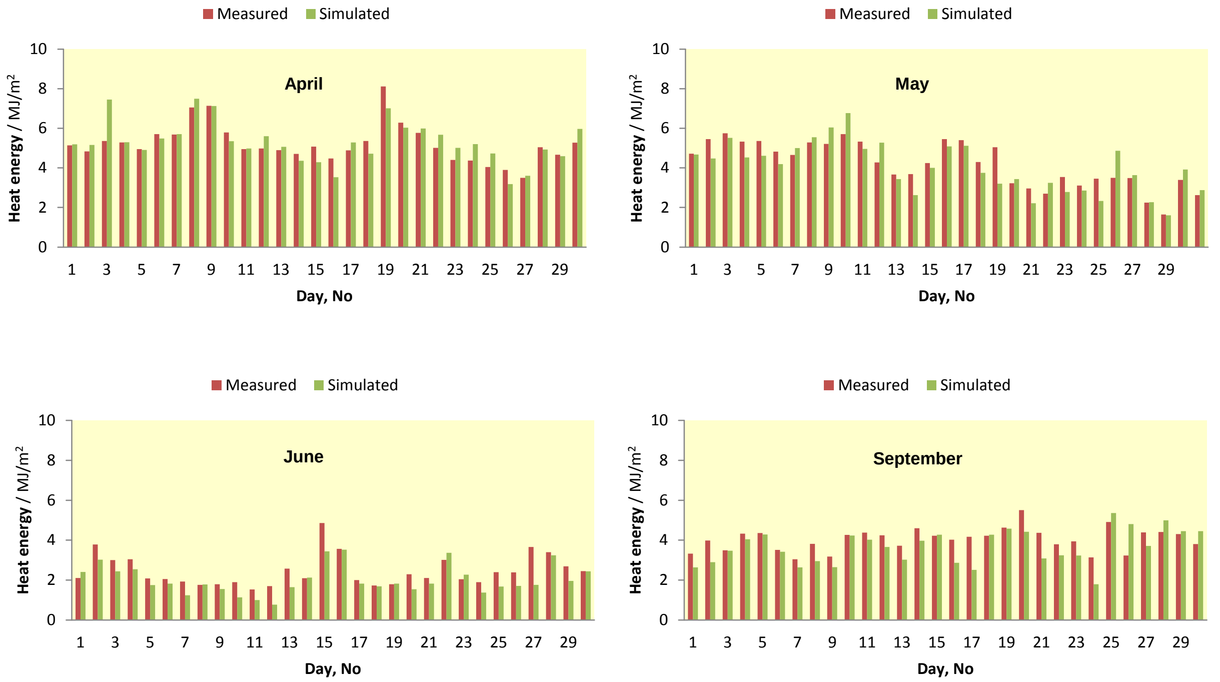

Figure 2 Measured and modelled heat energy supply for separate days during the months April, May, June and September

A regression between measured and modelled daily use of heat energy for the whole period between April and September is presented in Figure 3. The regression showed a fairly good agreement (R^2 = 0.75).

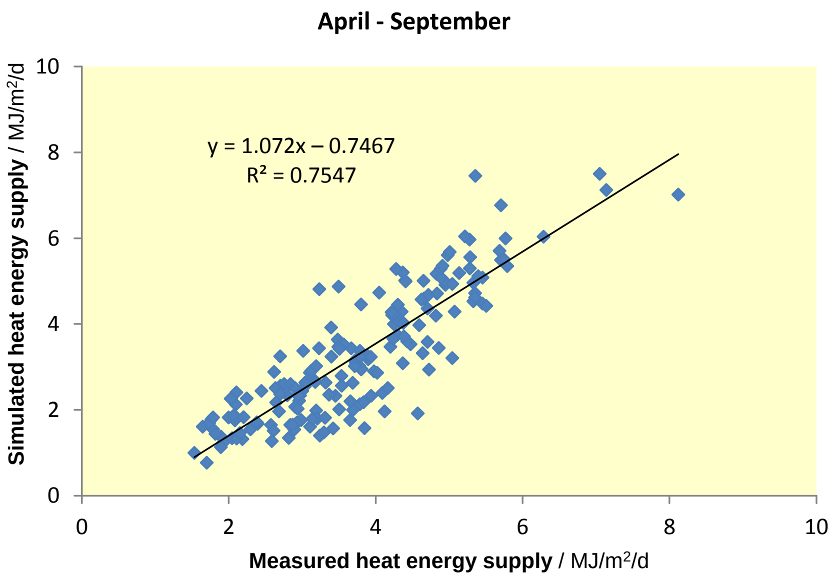

Figure 3 Measured versus modelled heat energy supply for all separate days during the period April, May, June, July, August and September

Figure 4 shows measured and modelled heat energy supply for some (three) separate days during the experiment. During these days the model predicted that there was no need for heating during hours close to noon when solar radiation was high.

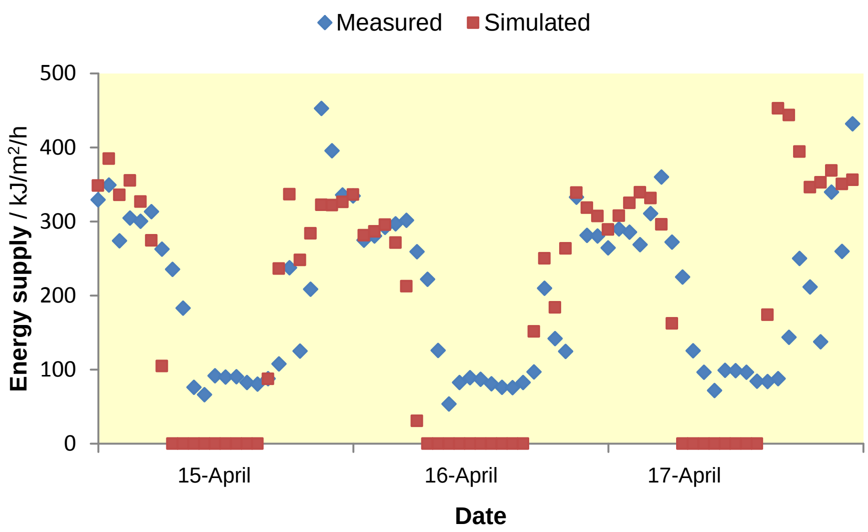

Figure 4 Measured and modelled heat energy supply for three days during the experiment

4 Discussion

Modelling greenhouse climate and heat energy use for greenhouses involves many factors. The model predicted the amount of heat energy needed in the greenhouse fairly well, but there are also indications that improvements of the model should be made. As can be seen in Figure 1, the agreements between predicted and measured values varied between months. Generally the climate inside the greenhouse was about the same for all months. However, months with smaller differences between humidity ratios (Δx, kg_{water}/kg_{air}) inside and outside the greenhouse (June, July, and August) had higher measured heat energy consumption compared to the modelled consumption. For colder months (April and September) with higher differences in humidity ratios the agreement between measured and modelled data was better. This may indicate that the model underestimates the transpiration of the plants and that more heat energy than modelled is used for dehumidification of the greenhouse. LAI (leaf area index) being an important factor for calculating the transpiration rate was in the study set to (assumed to be) 3.5 m^2 per m^2 plant mass area (or 3 m^2 of leaves per m^2 total greenhouse area with alleys included). This value may have been too low leading to an underestimated size of the transpiration. No measurements of the LAI were made.

Wind speed and/or precipitation may be some of the possible explanations for variations in differences between measured and modelled data for separate days (see Figure 2). In the model there are no equations predicting the influence of wind speed or precipitation on heat transfer from the cover materials. Further, the outdoor relative humidity used in the model was measured some distance away from the greenhouse where the humidity locally could have been different.

As can be seen for the selected days in Figure 4, predicted values indicate no need for supply heat at noon when the solar radiation contributes with extra heat inside the house. A higher transpiration rate than modelled can be one reason for this, but such data also indicate that heat storage in the heating system increases the energy use. Further, the data suggest that also heat storage in mass inside the greenhouse should be included in a model predicting heat energy use in greenhouses.

5 Conclusions

Development of the new Powersim model with inclusion of a model for transpiration of the plants for predicting the heat energy use in greenhouses is an ongoing process and the present study shows the performance at its present state. The following conclusions can be made:

- A large amount of factors influence the amount of heat energy used in a greenhouse. The model in the study seems to give a fairly good estimation of the heat energy use but there are indications that further improvements should be made.
- Transpiration of the plants has a strong influence on heat energy use in greenhouses at northern latitudes.
- The study indicate that heat storage in the heating system used in the studied greenhouse equipped with heating pipes and having higher inlet water temperatures increased the amount of heat energy used.

Further efforts should be made to improve the knowledge about mechanisms involved in transpiration, how the size of the transpiration rate could be easily estimated, and how it influences the energy use.

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