THE SOLAR GREENHOUSE: A SURVEY OF ENERGY SAVING METHODS

A. Saye, W.K.P. van Loon and G.P.A. Bot
Wageningen Agricultural University
Department of Agricultural Engineering
and Physics
Bomenweg 4, 6703 HD Wageningen,
The Netherlands

H.F. de Zwart
Institute of Agricultural and
Environmental Engineering (IMAG),
P.O. box 43, 6700 AA Wageningen,
The Netherlands

Keywords: Energy saving, greenhouse climate simulation, heating systems

Abstract

The solar greenhouse project is aimed at the development of a greenhouse concept for the Netherlands with zero-fossil energy consumption. The solar greenhouse is formulated as a combination of a low energy demand greenhouse, an energy recovery installation and an energy storage facility. In this paper, energy saving options such as new building materials, a dehumidifier, a heat pump and long term storage are studied. A simplified model is being developed in MATLAB to describe the total system. First calculations indicate that implementing the properties of the new building materials with high insulation, the installation of a dehumidifier, a heat pump and a storage system provides a significant reduction of the fossil energy use and an increase in the relative solar energy contribution to the total energy use.

1. Introduction

In the Netherlands, as in other northern countries, modern greenhouse horticulture is an energy-intensive economic activity. Fossil fuel consumption enables a favourable microclimate in the greenhouse with high yield. Due to growing public and governmental concern about the global effects of the combustion of fossil fuels, the Dutch government and horticultural industry have made an agreement to stimulate reduction of fossil fuel consumption. Energy-saving measures proposed in order to meet the short and middle term objectives were overviewed by De Zwart (1996).

On the long term the challenge is in a zero fossil fuel consumption greenhouse, indicated as the Solar Greenhouse (Bot, 1997). This greenhouse is basically designed with a very well insulated and high light transmittant cover, with climatization, climate control and energy management focussed at optimal crop growth and with exploitation of crop tolerance for variations of indoor climate.

Active dehumidification in connection to a heat pump and a long term storage system are important items in the climatization and the energy management. To investigate the potentials of this combination, a simplified simulation model of the energy and mass flows in the greenhouse, based on previous models (Bot (1983), Stanghellini (1987) and De Zwart (1996)) has been developed.

In this paper, simulation results of the energy need and heat loss will be presented to survey the above mentioned effects. This is evaluated in single and double covered greenhouses without and with a thermal screen. In this survey the emphasis is on the differences more than on the absolute levels.

2. Material

While we are interested in year-round performance of the system a steady-state model will be used to describe the energy and water vapour flows in the greenhouse. The basic model equations are the water vapour balance:

Proc. Int. Conf. and British-Israeli
Workshop on Greenhouse Tech. towards 3rd Mill.
Eds. M. Teitel, B.J. Bailey
Acta Hort. 534, ISHS 2000.

$$\phi_{m,\ transpiration} = \varphi\phi_{m,\ leakage} + \varphi\phi_{m,\ ventilation} \quad (1)$$

and the energy balance:

$$\phi_{E,\ solar\ radiation} + \phi_{E,\ heating} = \phi_{E,\ heatflow\ cover} + \phi_{E,\ leakage} + \phi_{E,\ ventilation} + \phi_{E,\ transpiration} \quad (2)$$

The emphasis is on well-insulated greenhouses. Therefore condensation on the cover is not taken into account.

2.1. Water vapour balance of the standard greenhouse

In well-insulated greenhouses humidity control is essential. The relative humidity set point is set to 85% corresponding to grower practice. At higher humidity levels, the greenhouse is dehumidified by ventilation or active dehumidification.

2.1.1. Transpiration of the crop

A simplified transpiration model was introduced based on data of Stanghellini (1987) in which transpiration of the crop $\phi_{m,\ transpiration}$ only depends on the solar radiation in the greenhouse. Crop status (LAI) is assumed to be constant over the year and so is independent of the growing season.

2.1.2. Water vapour flow by ventilation and leakage

The vapour flux due to ventilation $\phi_{m,\ ventilation}$ or due to leakage $\phi_{m,\ leakage}$ depends on the ventilation or leakage air exchange ($V_{ventilation}$ or $V_{leakage}$ ($m^3 s^{-1} m^{-2}$) respectively) and the concentration difference $h_{air,in}$-$h_{air,out}$ between inside and outside air (kg m^{-3}). So for ventilation:

$$\phi_{m,\ ventilation} = V_{ventilation} \cdot (h_{airin} - h_{airout}) \quad (3)$$

For $\phi_{m,\ leakage}$ of course $V_{leakage}$ is used.

2.2. Energy balance of the standard greenhouse

The energy balance represents the sensible heat flows affecting greenhouse temperature. For the evaluation of the energy need, temperature set points are needed. They were set at 17 °C and 20 °C for night and day respectively. If outside temperature is higher then set point temperature, the greenhouse temperature is set to the outside temperature.

2.2.1. Solar radiation

The solar radiation received at the surface of the earth ($\phi_{E,\ solar\ radiation}$, Wm^{-2}) varies with latitude, season, the time of the day and meteorological conditions. The amount of solar radiation entering the greenhouse depends on the transmissivity of the greenhouse cover. This depends on the type of material, cover geometry and solar radiation characteristics (Bot, 1983). In this survey, a constant transmissivity τ of 0.7 for a single cover and 0.65 for a double cover is used. The thermal screen is assumed to intercept 4% of the solar radiation (De Zwart, 1996).

2.2.2. Heat flow through cover

Heat is transferred through the greenhouse cover by convection, conduction and thermal radiation. This is represented in the thermal resistance R_{cov} ($W^{-1}m^2K$) of the cover linked to the overall heat transfer coefficient k_{cov} of the cover ($Wm^{-2}K^{-1}$):

$$R_{cov} = \frac{1}{\alpha_{in}} + \sum \left(\frac{\lambda}{\delta} + \alpha_{rad,int}\right)^{-1} + \frac{1}{\alpha_{out}} = \frac{1}{k_{cov}} \tag{4}$$

with: α_{in}: inside heat transfer coefficient due to convection and radiation ($Wm^{-2}K^{-1}$)
δ: thickness of the insulating material (m)
λ: thermal conductivity of the insulating material ($Wm^{-1}K^{-1}$)
α_{out}: outside heat transfer coefficient due to convection and radiation ($Wm^{-2}K^{-1}$)
$\alpha_{rad,\,int}$: radiative heat transfer coefficient between the transparent panes ($Wm^{-2}K^{-1}$)
Σ: summation over the insulating layers (double glass has one insulating layer)

The thermal resistance of the transparent panes themselves can be neglected. The total heat flow from the greenhouse to the outside through the cover ($\Phi_{E,\,cover}$, Wm^{-2}) can then be presented as:

$$\phi_{E,cover} = k_{cov} \cdot (T_{air\,in} - T_{air\,out}) \tag{5}$$

with: $T_{air,in}$-$T_{air,out}$: temperature difference between greenhouse and outside air (K).

A simple method to introduce a thermal screen in the greenhouse is by dividing the overall heat coefficient of the cover by a factor two during night-time (De Zwart, 1999). With double glass the thermal conductivity and thickness of the air layer are substituted.

2.2.3. Sensible heat exchange by ventilation and leakage

The sensible heat transferred by the ventilation air exchange ($W\ m^{-2}$) depends on the ventilation air exchange $V_{ventilation}$ ($m^3s^{-1}m^{-2}$) and on the temperature difference between inside and outside air. The sensible heat exchange due to leakage can be calculated accordingly.

$$\phi_{E,ventilation} = V_{ventilation} \cdot c_{air} \cdot \rho_{air} \cdot (T_{airin} - T_{airout}) \tag{6}$$

with: c_{air}: specific heat of air at constant pressure ($J\ kg^{-1}K^{-1}$)
ρ_{air}: density of air ($kg\ m^{-3}$)

According to De Zwart (1996), for an average greenhouse the leakage air exchange through the cover (V_{leak}) equals a factor of $1.5 \cdot 10^{-4}$ ($m^3\ m^{-3}$) multiplied by the wind speed (m/s). The ventilation air exchange is calculated by the steady state model to remove excess heat or excess water vapour at the given set points.

2.2.4. Latent heat of transpiration

Part of the energy absorbed by the crop is transferred to latent heat due to transpiration. This energy flux follows from the crop transpiration (section 2.1.1) according to:

$$\phi_{E,\,transpiration} = \phi_{m,\,transpiration} \cdot c_{vapor} \tag{7}$$

with c_{vapour}: latent heat of vaporisation of water ($J\ kg^{-1}$)

2.2.5. Heating

The energy needed to heat the greenhouse to the given set point temperature is calculated from the steady state energy balance (eq. 2). Using this value and assuming an efficiency of a gas boiler of 90%, the amount of fossil fuel (kg year^{-1}m^{-2}) is calculated.

2.3. Solar greenhouse

In the solar greenhouse a dehumidifier, a heat pump and a long term storage facility are added. The intention of the solar greenhouse is to use solar energy in a more efficient way. By means of the dehumidifier, latent energy that otherwise would have been lost can be regained as sensible heat. The cold surface dehumidifier principle was chosen. The heat pump driving this dehumidifier releases the captured energy at a higher temperature. If this energy is not immediately needed for heating, the heat surplus is stored for later use. In the following sections, the modifications in the energy and water vapour balance will be briefly explained.

2.3.1. Energy balance

The energy balance for the solar greenhouse extends itself with a sensible heat flow towards the cold surface dehumidifier, a heat flow from the heat pump and a heat flow from the long term storage:

$$\phi_{E,\,solar\ radiation} + \phi_{E,\,heating} + \phi_{E,\,heatpump} + \phi_{E,\,storage} = \phi_{E,\,heatflow\ \mathrm{cover}} + \phi_{E,\,leakage} + \phi_{E,\,ventilation} + \phi_{E,\,transpiration} + \phi_{E,\,dehumidifier} \quad (8)$$

The heat flow to the dehumidifier, $\phi_{E,dehumidifier}$ (Wm^{-2}) depends on the capacity of the dehumidifier. This is represented as a cold surface. Under normal greenhouse conditions it can easily be calculated that sensible and latent heat flow to the dehumidifier are about equal. The sensible heat flow is calculated according to:

$$\phi_{E,\,dehumidifier} = k_{dehumidifier} \cdot (T_{airin} - T_{dehumidifier}) \quad (9)$$

The heat flow from the heat pump, $\phi_{E,heatpump}$, depends on the coefficient of performance of the heat pump (COP) equation 10:

$$COP = \frac{\phi_{E,\,heatpump}}{W} = \frac{\phi_{E,\,dehumidifier} + W}{W} \quad (10)$$

with W: power input to heat pump (Wm^{-2}). The power is obtained from fossil or sustainable energy depending on the mechanism used to drive the heat pump (gas motor, electricity, wind power).

The amount of heat needed from the long term storage, $\phi_{E,storage}$, depends on the remaining heat demand of the greenhouse and the available energy which depends on the amount of heat stored and released.

2.3.2. Water vapour balance

The water vapour flow to the dehumidifier $\phi_{m,dehumidifier}$ is the additional factor in the water vapour balance:

$$\phi_{m,\,transpiration} = \phi_{m,\,leakage} + \phi_{m,\,ventilation} + \phi_{m,\,dehumidifier} \quad (11)$$

It is calculated from equation 11 to absorb the excess water vapour.

3. Method

The steady-state model is used for the comparison of the year-round performance of various greenhouse systems. The hourly meteorological data were taken from the SEL-year, a database of hourly weather data of a standard Dutch climatological year (Breuer and Van de Braak, 1989). Four different types of greenhouses will be compared with regard to energy use and loss as briefly explained in Table 1.

3.1. Standard greenhouse with boiler

To determine the energy demand for the standard greenhouse, the ventilation flux is calculated from the vapour balance as well as from the energy balance. An iterative calculation scheme is used to take into account that exceeding the maximum ventilation rate causes a raise of the temperature and vapour content of the air. Eventually, the highest value from the two balances is taken as ventilation rate. Introduction of this value into the energy balance gives the amount of required heating with fossil fuels to keep the greenhouse at a constant temperature.

3.2. Greenhouse with boiler and dehumidifier

The introduction of a dehumidifier in the greenhouse changes the previous iterative calculation scheme. For this type of greenhouse, first the ventilation need is calculated from the energy balance. This ventilation need is used in the mass balance and then the surplus moisture is absorbed by the dehumidifier within its capacity. The rest of the heat needed is provided by a boiler. The dehumidifier is connected to a gas-driven heat pump. The heat absorbed by the dehumidifier is wasted.

3.3. Greenhouse with boiler, dehumidifier and heat pump

The use of the heat pump as a secondary heat source adds an energy flux to the energy balance. For this type of greenhouse, it is assumed that all the recovered heat is brought back into the greenhouse.

3.4. Solar greenhouse

The introduction of an aquifer will provide a storage system for the surplus heat. In the same way as for the greenhouse with dehumidifier and heat pump, the ventilation losses and dehumidifier activity is calculated. Depending of the heat need in the greenhouse, the recovered energy is brought back to the greenhouse or stored for later use. When stored, a heat loss due to long term effects of 20% was taken.

In these calculations, the remaining heat need of the greenhouse is expressed as fossil energy need. In the future it will be clear if this remaining need can be covered by renewable energy.

4. Results

The standard greenhouse without energy saving options has a fossil fuel use of 1.75 GJ $year^{-1}m^{-2}$, and a relative solar energy contribution of 57%. These are pretty realistic results (De Zwart, 1996). To show the effects of varying insulation and of various greenhouse types, we will present one greenhouse type (greenhouse with dehumidifier and heat pump) with varying insulation and one type of insulation (thermal screen, as the most common energy saving option) with varying greenhouse types.

4.1. Effect of insulation

The calculated energy needs and the heat loss are shown in Figure 1 and 2, comparing single cover, double cover and thermal screen.

The use of different insulation methods affects the energy budget of the greenhouse (Figure 1). A higher insulation causes a decrease of the transmissivity of the greenhouse which causes a decrease in the absolute solar energy use in the greenhouse. On the contrary, the relative solar energy use increases because the insulation causes a higher reduction of the fossil energy use. A higher insulation of the cover lowers the heat loss through the cover (Figure 2).

4.2. Effect of a dehumidifier and heat pump

Tables 2 and 3 show the influence of a dehumidifier and heat pump on the energy flow in the greenhouse. A dehumidifier lowers the need for ventilation to reduce the amount of vapour in the greenhouse. If the heat absorbed by the dehumidifier is recovered and brought back into the greenhouse, the total energy need decreases significantly, due to a lower total energy loss. Use of the recovered heat also decreases the fossil fuel use, even taking into account the extra energy used by the compressor. When the heat is not recovered, the ventilation need is lower, but the heat losses of the heat pump are high (0.97 MJ $year^{-1}m^{-2}$). This causes a higher use of fossil energy and an increase in the total energy need.

The calculations in Tables 2 and 3 also present the solar greenhouse as the least energy intensive greenhouse. The heat pump in combination with storage provides a secondary heating system that gives a further decrement in the fossil energy use. This creates an increase in the relative amount of solar energy used in the greenhouse.

5. Conclusion

First general calculations are optimistic for further investigation of the possibilities of a solar greenhouse. Relatively simple options increase the relative solar energy contribution from 57% to 80% and reduce fossil energy consumption towards 37%. Further improvements will be found in higher insulation and more transparent materials. In the research, emphasis will be on modelling the dehumidifier, heat pump and storage system and on introducing further details on the horticultural aspects.

For a real zero-fossil greenhouse (solar greenhouse) the work to drive the heat pump has to be delivered from sustainable energy sources.

Acknowledgements

This research was financed by the E.E.T. research program funded by the Dutch Ministries of EZ (Economic Affairs), of OCW (Education) and of VROM (Environmental Affairs).

References

Bot G.P.A., 1983. Greenhouse climate: from physical processes to a dynamic model. Ph.D. Thesis, Wageningen Agricultural University, Wageningen: 240 pp.

Bot G.P.A., 1997. Project Zonnekas (in Dutch: the Solar Greenhouse Project). Wageningen Agricultural University. Internal report. 60 pp.

Breuer J.J. and Van de Braak N.J., 1989. Reference year for Dutch greenhouses, Acta Hortic. 248:101-108.

De Zwart H.F., 1996. Analysing energy saving options in greenhouse cultivation using a simulation model. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands: 236 pp.

Miguel A.A.F., 1998. Transport phenomena through porous screens and openings, from theory to greenhouse practise. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands: 129 pp.

Stanghellini C., 1987. Transpiration of greenhouse crops, an aid to climate management. Ph.D. Thesis, Wageningen Agricultural University, Wageningen:150 pp.

Tables

1. Description of the differences between the three types of greenhouses discussed in this article

Type	Features
Standard greenhouse	boiler
Greenhouse with dehumidifier	boiler, dehumidifier
Greenhouse with dehumidifier and heat pump	boiler, dehumidifier and heat pump
Solar greenhouse	dehumidifier, heat pump and aquifer

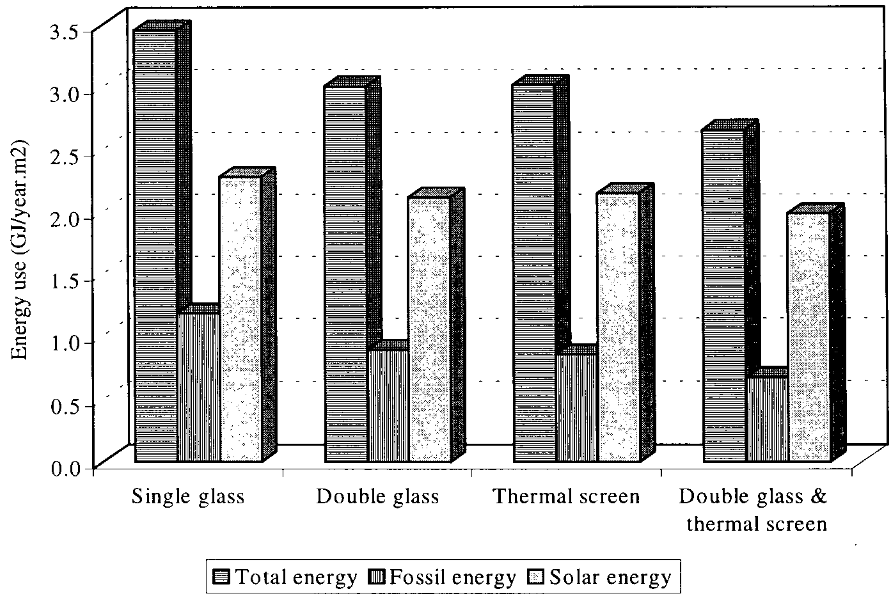
2. Total energy use and components for the four different types of greenhouses

Type greenhouse	Total energy (GJ $yr^{-1}m^{-2}$)	Fossil energy (GJ $yr^{-1}m^{-2}$)	Solar energy (GJ/$yr^{-1}.m^{-2}$)	Solar energy (%)
Standard greenhouse	3.59	1.44	2.15	60
Dehumidifier	3.88	1.73	2.15	55
Dehumidifier + heat pump	3.01	0.85	2.15	77
Solar greenhouse	2.95	0.80	2.15	79

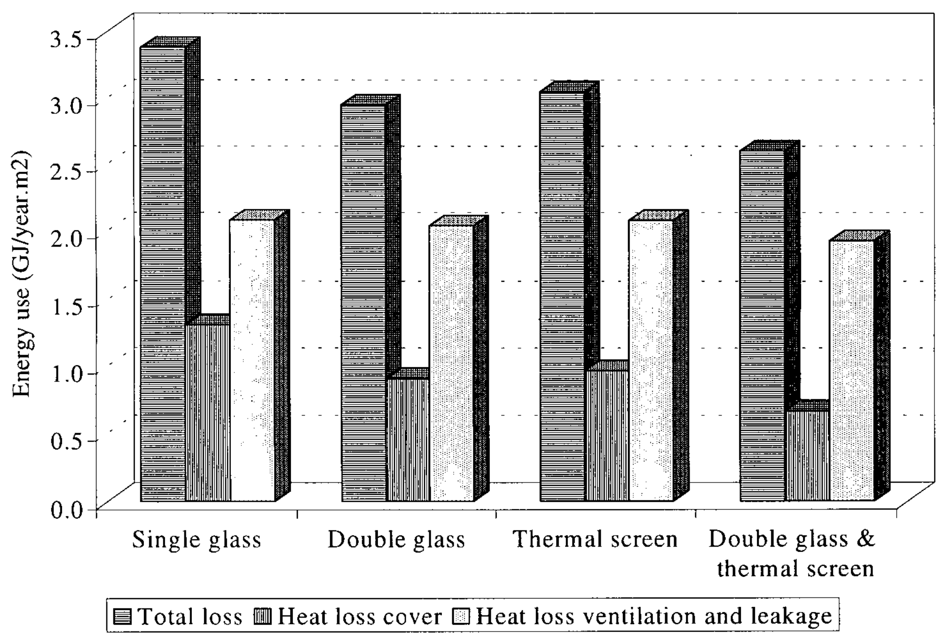
3. Energy loss (GJ $yr^{-1}m^{-2}$) of components for the four different types of greenhouses

Type greenhouse	Heat loss cover	Heat loss ventilation and leakage	Other heat loss
Standard greenhouse	0.97	2.58	0.00
Dehumidifier	0.97	1.93	0.95
Dehumidifier + heat pump	0.97	1.96	0.00
Solar greenhouse	0.97	1.93	0.02

Figures



1. Energy need of the greenhouse with dehumidifier for different insulation methods



2. Energy losses of the greenhouse with dehumidifier for different insulation methods