Temperature and Humidity Control in the Watergy Greenhouse

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Abstract

A closed greenhouse with passive cooling and dehumidification strategy is described, allowing a reduction of water consumption of 75% and continuous plant production even during hot summer conditions in Southern Spain. Main points of examination are how the air temperature and humidity in the closed greenhouse could be kept in the allowed range without using external energy except solar energy and how a growth cycle of crop could be held successfully and plants used in a satisfying way to purify water.

INTRODUCTION

Closed greenhouses are commonly discussed as a possibility of a more resource efficient horticultural production in terms of water and energy. Water is the main limiting factor of growth in arid areas worldwide, as it is the basis for food production and principal human life support. Global population growth provokes new technologies not only for more efficient ways of water use and higher productivity of agriculture, but especially for future development of non cultivated land. Growing prices for fossil energy are the main reason for diminished competitiveness of horticultural production in Central Europe, where heating demand during winter is the main problem.

In a closed greenhouse, air exchange with the ambient is minimised, evaporated water is recycled by condensation processes and the solar heat load is partially captured and stored, and can be used for heating processes in delayed time. Anyway, artificially cooling a greenhouse needs further mechanical energy (i) for internal air circulation between the vegetation area and a heat exchanger, (ii) to drive a heat pump for cooling and/or (iii) to drive circulation pumps for transport of cooling or heating media. Because of this, until now only little reduction of primary energy consumption has been gained and water recycling had to be paid for by an additional need for energy.

Further advantages of a closed greenhouse are reduction of pest control, efficient use of CO_2 and the possibility of enhanced CO_2 concentration in the closed environment.

In comparison with previous concepts of closed greenhouses (Opdam et al., 2005) that used conventional air conditioning equipment like ventilators and heat pumps, the aim of the Watergy concept (Buchholz, 2000) is to provide passive ventilation and cooling strategies mainly based on solar energy, using the effect of buoyancy for air movement and using the temperature differences between day and night as a source of coolant capacity.

MATERIALS AND METHODS

The Watergy system has been designed on the base of computational simulation of the energy and water balances including air mass transfer (Jochum and Buchholz, 2005). The system is currently in the state of development since the year 2003 when a prototype at the Experimental Station of Cajamar in the province of Almeria/Spain, was constructed in a European Union funded research project. The basic production surface is 200 m². It has been working in a closed state for about two years with French beans, bush beans and okra.

The main innovative element is a cooling tower in the centre of the greenhouse where during the day time, hot air rises from the vegetation area, through the roof area into the tower (Buchholz et al., 2005). To increase the energy and water content of the rising air, it is further humidified in the roof area by sprinklers on an inner roof plastic layer. Figure 1 shows a scheme of the circulation of the air inside the greenhouse.

From the top of the tower, the air falls back to the bottom of the greenhouse as it is cooled in a duct by a heat exchanger. The cooling media is water and is provided from 3 storage tanks of 5 m³ each outside of the greenhouse. Through the cooling process, the humid air condenses and the evaporated water from irrigation and from the sprinklers can be recycled.

During the night, the heated water from the store flows in reverse direction through the heat exchanger, in order to release the heat back to the greenhouse and to cool the store. The heat exchanger is then humidified by further sprinklers, in order to increase the heat release with additional evaporative cooling.

As they are separated from the vegetation, both sprinklers at the inner roof and in the tower can be fed with saline water in order to integrate a desalination function. Water can also be upgraded during the process, if impure water is used for irrigation.

RESULTS AND DISCUSSION

Cooling process

The main aim of the cooling process is to keep the air around the vegetation at a level which allows optimum growth conditions and to hinder short term overheating that would kill plants or parts of them (especially flowers). By having an artificial supply of CO_2 at concentrations between 600 and 1200 ppm (which is between two and three times more than the atmospheric level), the maximum optimum growth temperature is also lifted from 24 to 29° C.

The cooling system was extended with further measures in the hottest season, like whitening of the southern facade and the installation of a shading fabric under the inner roof. With all these activities, a permanent cultivation within the closed greenhouse was possible, having healthy vegetation even through the hot summer period.

An example of the cooling operation in the closed greenhouse is shown in Fig. 2 for a period of 10 days during April 2005. The temperature spectrum in the greenhouse (T_{gh}) is shown. The temperatures during daytime range from 20 to 35°C. The cooling in this period was only achieved with the cooling tower without any light reduction (later, the southern facade was whitened). The effect of the cooling tower can be seen as the difference between T1 (air temperature at the top of the tower), that should be maximised for optimum heat density in the store, and T2 (at the bottom of tower) that should be minimized for optimised greenhouse cooling and dehumidification. T0 shows the average temperature in the store.

An enhanced efficiency of the passive cooling can be achieved by increasing the heat released at night with the sprinkling of water in the heat exchanger, as was done in the summer. However, there is a limit to the heat release, as shown in Fig. 3. The temperature of the cooling media (blue) cannot go below the external night time temperature values. Overlapping of the two curves shows the best heat release performance. This figure illustrates, that a climate of large day/night differences in temperature (like a desert climate) is favourable for the passive cooling strategy, as long as the daytime temperature does not exceed a certain value.

Dehumidification process

To allow continuous plant growth in the greenhouse, the internal air needs permanent dehumidification in parallel to the evaporation processes. This is realised by condensation on the coldest surfaces in the system, especially on the heat exchanger (during daytime) and the outside surface (during night). The effect can also be used for water recycling and upgrading (Zaragoza et al., 2006).

The average water demand for irrigation in the Watergy prototype is about ~1.5 L/m^2 d (relatively low due to higher relative humidity in the greenhouse) and the water recycling rate (from condensed water) is 65%. Further, 10 % of the water was recycled by collection of water from soil drainage. In comparison with open field agriculture, this is already a minimisation of water demand of 90%. This can already be considered as a water autarky mode, as the remaining water demand (resulting from losses in the condensation collection process and humidity losses by air exchange through the remaining leakages) can be provided by the collection of rain from the surface (in the given climate of southern Spain).

The condensation process goes parallel to the cooling process, but other than the release of heat, condensation appears only at the coldest parts of the surfaces. It should not appear on the vegetation surfaces as here, the main part of the evaporation has to take place.

As for optimum plant growth, a maximum temperature is set and the temperature where condensation takes place is generally under this limiting value. This is the main difference to a solar still, where condensation during daytime can appear on the outside cover. The cover is irradiated by the sun and relatively hot, but the internal temperatures can rise beyond the surface temperature. In the energy balance of the greenhouse, only the heat that is released by the heat exchanger is turning to condensation.

The energy balance (Fig. 4) for a period of 5 days in April 2005 is calculated on the basis of temperature measurements (greenhouse and ambient air temperatures, water temperatures from and to the heat store and soil temperatures). Furthermore, leakage air exchange has been calculated from CO_2 concentration decay measurements in the empty greenhouse under different climatic situations and wind speeds. The energy transfer of air exchange is based on inside/outside air temperatures and humidity as well as the mass flow of the leakage air exchange.

The daytime balance shows four major paths of heat flow out of the greenhouse: through the cover, into the soil, the remaining convection to the ambient and between the greenhouse and the heat store.

It is interesting to see, that the part of the active thermal control is much less than the direct heat losses, but during daytime, only the heat exchanger is leading to condensation, as the heat transfer works at lower temperatures.

In this context, the energy balance is the base information for further improvements of the system. Increasing the part of the energy that is transferred to the heat storage will allow further reduced air temperatures and lower air humidities in the vegetation area.

Furthermore, having lower humidity at the cooling duct outlet will increase the transpiration of the plants, which will, in a chain reaction lead to furthermore evaporative cooling and will enable a broader variety of potential crops to be suitable for the system due to the lower temperatures. A second effect will be an increased condensation and water recycling rate.

There are several ways of increasing the energy transfer to the store:

- A higher air circulation rate will lead to higher transport of water vapour. It can be reached with a higher tower, a lower cooling water temperature and also with an improved heat exchanger with lower air resistance.
- A larger store can provide more cooling water during the hottest periods of the summer, where sufficient cooling is crucial, but where recycled water also has the highest value. The analysis of the measurements showed that the volume of the thermal storage was not big enough to provide sufficient cooling through all the afternoon during the hottest months. The missing cooling load was then provided by temporarily extending the heat store by the use of cooler water from a large water reservoir.
- Improved cooling through the night can provide a lower cooling temperature, that is leading directly to more condensation and also induces a higher air circulation rate. It could be reached by opening the system during night
- Figure 5 shows that the difference between the humidity of the greenhouse and the ambient air is much lower at night than during the day, so that the effect of water losses would be much lower if the grenhouse was opened at night. This has not been tried, because the effect of pest control and CO_2 enrichment by using a closed environment was also being tested. A further improvement in the night cooling of the store could be the use of a more efficient heat exchanger and another position for the heat exchanger, e.g. outside of the greenhouse.
- An improved post humidification in the roof zone will also improve the energy transfer into the store, as if the air enters the cooling duct at maximum humidity (near saturation), more condensation appears at the same cooling temperatures and more latent heat is released.

Plant performance

After having a successful harvest of green beans during winter 2004, a second generation of beans in springtime did not succeed as the flowers faded when the early summer came. The plants then were replaced with Okra, that developed very well all though the summer and fall, being replaced with green beans again for another successful winter cycle.

Until now, all vegetation periods were performed without any pesticides. They were not needed due to the closed state of the building (no insects could enter).

Also, no problems with fungi were observed. It looks, that even having quite high humidities, the period of high temperatures during midday helps to systematically dry the plant's surfaces.

Pest control is another big success for the project, as it shows that the system can provide an environment for the production of higher quality fruits.

CONCLUSIONS

The project is aimed to find short term solutions for the energy demands and ecological impacts of horticultural production. The capacity of controlling the climate of closed greenhouses using only solar energy, and the water purification are of great interest in the development of a more sustainable intensive horticulture. As the same principle leads to cheaper heat generation in Central and Northern Europe, it can result in a basic technology for sustainable agriculture.

The first prototype is a closed greenhouse for solar thermal energy capture, water recycling, water desalination and advanced horticultural use. It has been constructed in Almería (Southern Spain) and has been under evaluation for two years. The main points to examine in the tests were: (i) whether the air temperature and humidity in the closed greenhouse could be kept in the allowed range without using external energy except solar energy; (ii) whether a growth cycle of a crop could be held successfully and plants used in a satisfying way to purify water.

The experiments did show a very acceptable effectiveness in temperature control, as having a closed greenhouse in the hot climate of the region. The comparison with passive systems placed in the surrounding area is impressive, where overheating does not allow any cultivation during summer. Creating a climate allowing at least normal productivity of plant growth and around 75% reduction of water consumption without the use of additional energy is a very big success. Though adjustments for better performance must be made, together an application of the knowledge obtained and a simplification of the prototype would turn the concept into a valid commercial product.

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Figures

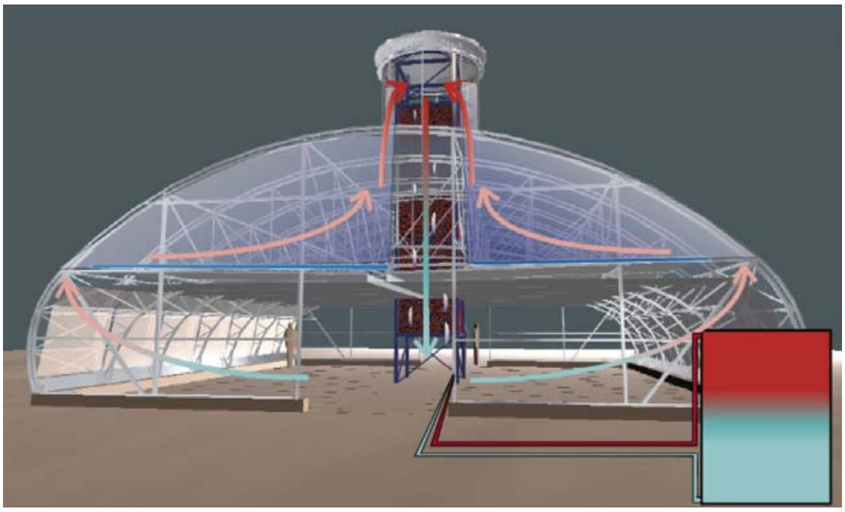

Fig. 1. Air flow scheme of the Watergy greenhouse.

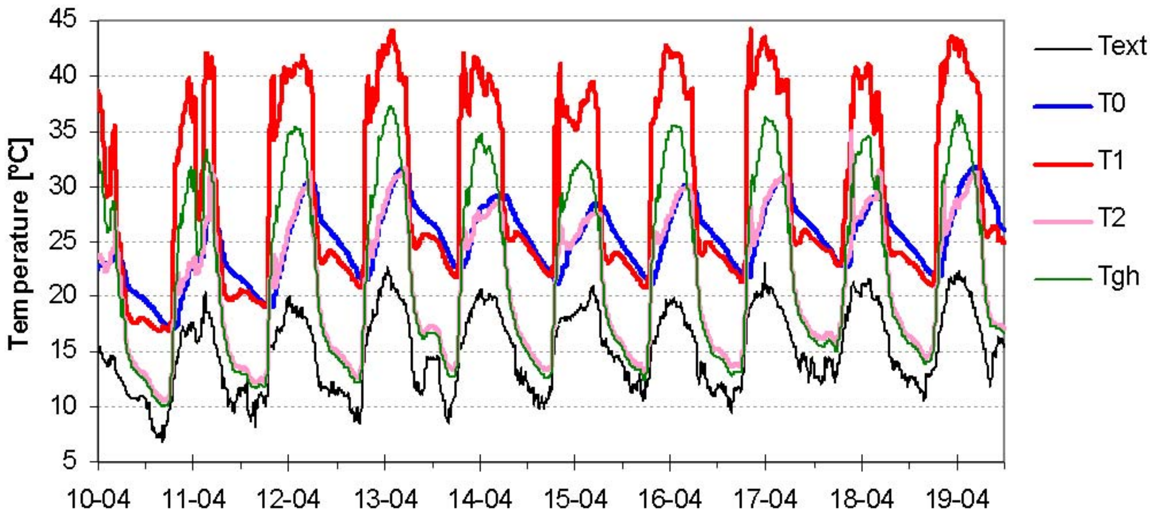

Fig. 2. Temperatures in the system during April 2005. T_{ext} = air temperature of the environment, T_0 = average storage temperature, T_1 = air temperature at cooling duct entry (top of tower), T_2 = at cooling duct outlet (bottom of tower), T_{gh} = in the greenhouse.

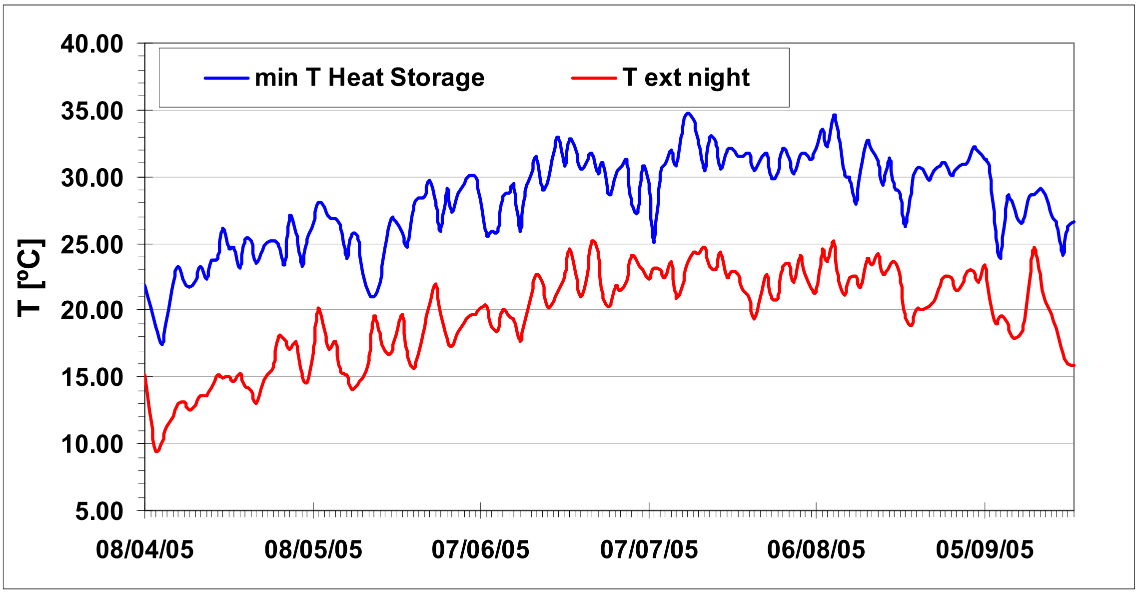

Fig. 3. Minimum temperature of the heat storage compared with outside temperature at night through summer 2005.

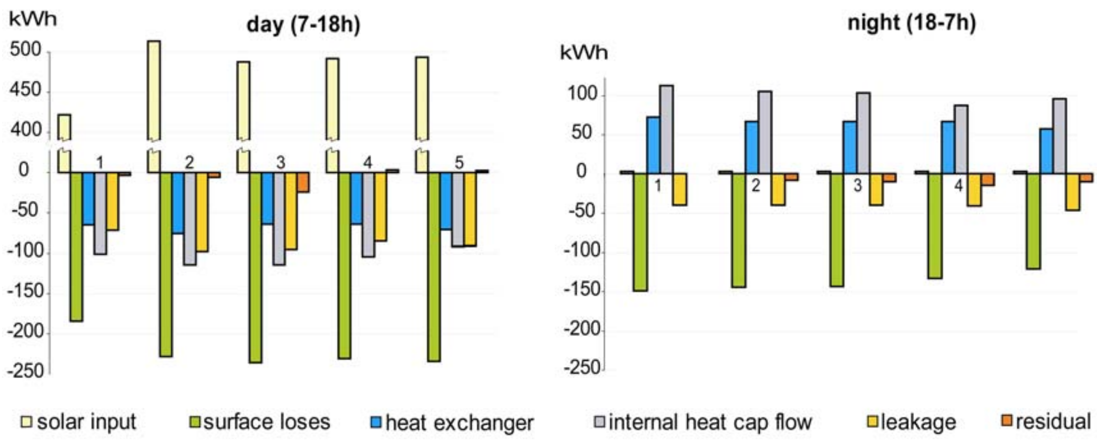

Fig. 4. Energy balance of the greenhouse.

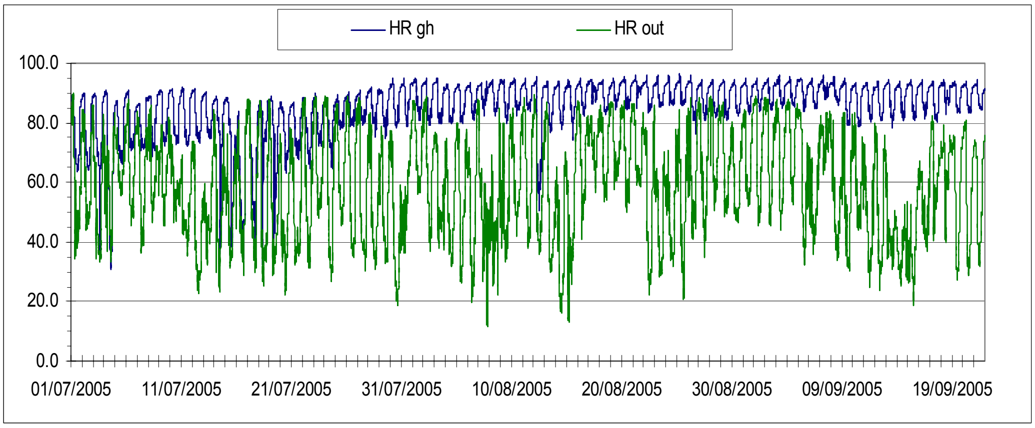

Fig. 5. Relative humidity of the greenhouse (HR gh) compared with the ambient (HR out) July - September 2005.

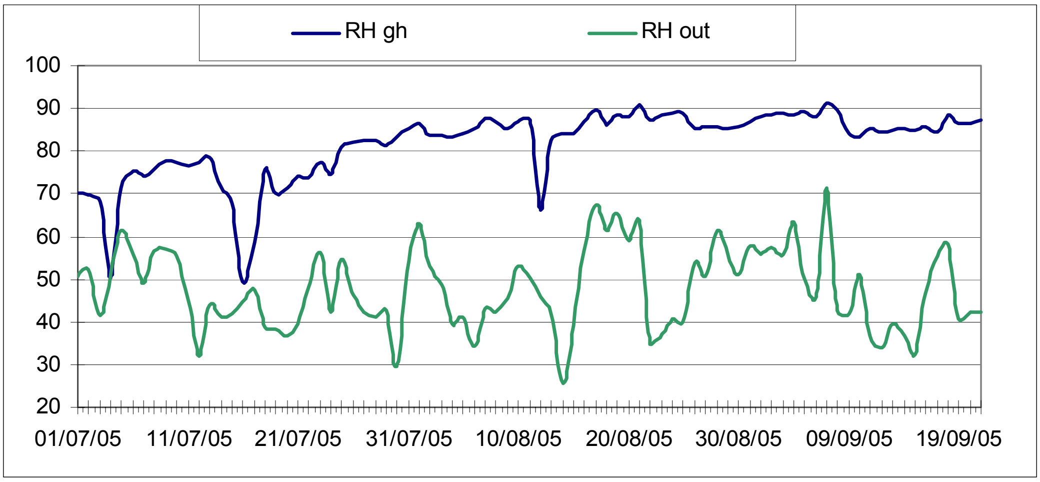

Fig. 6. Mean values of relative humidity in the greenhouse (RH gh) compared with the outside (RH out) during the day through the summer 2005.

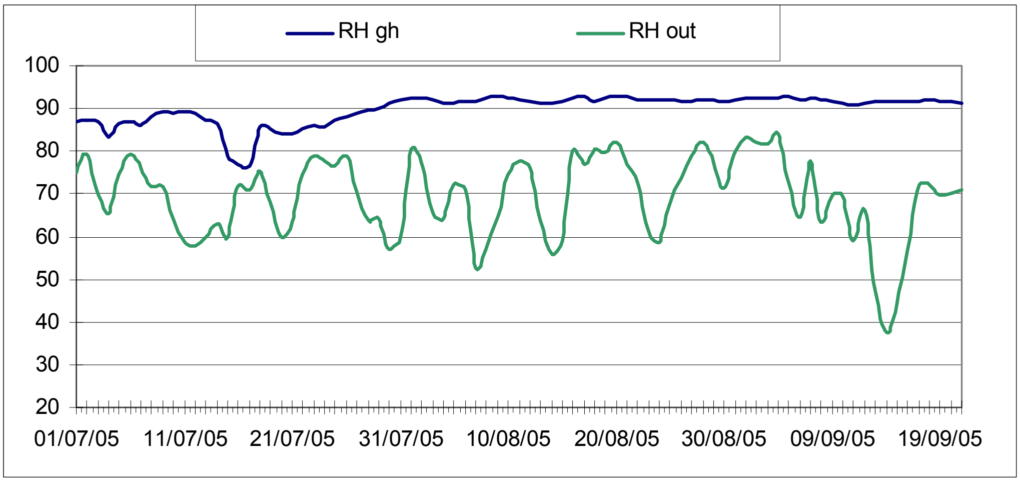

Fig. 7. Mean values of relative humidity in the greenhouse (RH gh) compared with the outside (RH out) during the night through the summer 2005.