Closed Greenhouses for Semi-arid Climates: Critical Discussion Following the Results of the Watergy Prototype

G. Zaragoza
Estación Experimental Fundación Cajamar
El Ejido-Almería, Spain
gzaragoza@cajamar.es

M. Buchholz
Technische Universitaet Berlin
Dept. of Building Technology and Design
Berlin, Germany

Keywords: Closed greenhouse, water conservation, CO_2 enrichment, anti-fog cover

Abstract

The Watergy first prototype of a closed greenhouse minimizes the use of water and energy. It has been operating since autumn 2004 in the semi-arid region of El Ejido in Almería, Spain. A balance with the main conclusions from the evaluation of the prototype is presented. A healthy crop has been maintained inside the greenhouse during all seasons, improving the production with respect to traditional open greenhouses and achieving a drastic reduction of the water consumption (about 80%). One of the main challenges has been to keep the temperature below 35ºC with its passive cooling system. Several strategies have been followed and the results are outlined. Another sensitive point has been the short durability of the anti-fog property of the plastic cover material. The implications of both aspects in further designs are discussed.

INTRODUCTION

Closed greenhouses are contemplated as a solution for the growing problem of the scarcity of water resources in the semi-arid regions where most of the current development of greenhouses is taking place. Further advantages of the concept are the possibility of turning the greenhouse into a CO_2 sink, with the bonus of an increased production as well as the avoidance of pesticide use. However, the main challenge to operate a closed greenhouse under these climatic conditions is the strong necessity of cooling, which requires large amounts of energy consumption. This is not the case of the Watergy prototype, where cooling is achieved with a passive system based on: (i) natural convection established by a tower; (ii) heat dissipation based on the lower night temperature as a source of cooling (Buchholz et al., 2005). While the energy conservation is its main strength, it is also the reason of one of its weaknesses. The lack of a heat pump or a lower temperature source of cooling makes it very complicated to keep the optimal conditions for crop growth inside the greenhouse during the warm season. Although this has been taken into account in the horticultural concept and heat tolerant plants are considered for the warm season, additional measures are required. Whitening the cover with calcium carbonate, a standard practice in open greenhouses in semi-arid regions in spring and summer, can solve the problem. However, with the high CO_2 concentration levels in the closed greenhouse, this practice reduces the system's yield potential. Another aspect that decreases the efficiency of the prototype is the quality of the cover material. A good anti-fog material is essential so that the continuous condensation does not reduce light transmission and the condensate can be collected.

In this paper, both aspects are evaluated based on the experimental results of the Watergy prototype. Recommendations for future performance and/or design of closed greenhouses are presented and discussed.

MATERIAL AND METHODS

The prototype was designed to minimize the energy consumption by using the natural buoyancy to circulate the air through a heat exchanger contained inside a tower located at the centre of the greenhouse. The heat extracted from the closed greenhouse during the day is dissipated during the night to restore the cooling capacity (Buchholz et al., 2006). The prototype was also contrived to maximize water treatment, using all the heat stored outside the greenhouse to upgrade water. Condensation takes place on the surface of the heat exchanger during the day but also on the inner side of the cover. For the cover, three different products have been tried. The first two were standard anti-fog materials: a three-layer combination (200 μm thick) of polyethylene on the outside and ethylene vinyl acetate (EVA) with anti-fog additive on the inside. A special five-layer plastic (also 200 μm thick) with more additive-filled layers has also been tried.

The prototype (cultivation area of 200 m^2) has been operating in Almería, Spain, since October 2004. A high concentration of CO_2 (about 1000 ppm) was maintained continuously inside the closed greenhouse using a standard commercial injection system. Climatic data were monitored, together with yield results. Continuous cultivation was carried out by using the technique of inter-planting, which alternates cycles of crops. Beans (*Phaseolus vulgaris*) were grown during the whole year with the exception of the summers, when okra (*Abelmoschus esculentus*), a C4 plant more tolerant to high temperatures, and kenaf (*Abelmoschus cannabinus*), a biomass crop interesting for its high quality fibre, were grown.

RESULTS AND DISCUSSION

Agronomic results

Crop was produced in the closed greenhouse system in all seasons, with no use of pesticides and a considerable saving of water. The water cycle was closed, with the recovery of up to 80% of the total irrigation water by lixiviation and condensation (further reused in irrigation), and the added collection of rainfall (Zaragoza et al., 2007). Yield and water use efficiency were larger than those in open greenhouses (Buendía et al., 2007; Zaragoza et al., 2008a), not only for fruits but also for biomass growing. The production of kenaf was increased by a factor of 2 in comparison with annual cropping in open air, and in a shorter 3 month cycle. This shows the opportunity of much larger productivity in the closed greenhouse cultivating the whole year with increased CO_2 concentration.

However, the potential for larger yields was not fully exploited. First, the climatic conditions were not optimized for fruit production. As discussed in the next section, the level of whitening that needs to be applied during the warm season can be further decreased. But most importantly, the agronomic aspects were not tuned to take advantage of the much larger CO_2 concentration inside the closed greenhouse. The cultivars grown so far were the ones adapted to open greenhouses in the area, where if not so much the temperatures, the humidity conditions are considerably different. Also, the standard crop management were employed, not adapted to the particularities of the closed greenhouse, with an increased CO_2 concentration but also a decreased evapotranspiration levels. These aspects are currently unclear in closed greenhouses. While the agronomic management in open greenhouses has been optimized during several decades, the most suitable cultivars and/or growing practices for closed greenhouses are yet to be determined.

Climate control

The climatic conditions held inside the Watergy closed greenhouse were good enough for cultivation all year long. Relative humidity was kept between 65% and 85% by the system, except during the first winter when the density of tall plants was too high, i.e., 2 plants/m^2 of French beans. In that extreme case with maximum leaf area index, relative humidity was between 85% and 95%, and still no fungal diseases occurred.

As for the temperature, minimum values were usually 3-4 ºC higher than outside, due to the closure of the greenhouse and the thermal mass of the soil. During the day, the cooling system maintained the maximum temperatures not more than between 6 and 10 ºC above outside temperatures. This was achieved with no use of energy other than what the pump required to circulate water through the heat exchanger and a small fan incorporated on the top of the heat exchanger to compensate for the pressure drop of non-performing parts which were too complicated to remove. While it was good enough to guarantee plant growth, sometimes these conditions were above the optimum for maximum productivity. The purpose of the Watergy prototype is not to guarantee the perfect climate for maximum plant performance. It is an impossible task without the use of a heat pump or a further source of cooling. Nevertheless, some measures can be taken to improve the climatic conditions, and therefore the productivity of the closed greenhouse.

First, the thermal thresholds should be defined. In standard open greenhouses in Spain, 35ºC is usually considered as the maximum temperature that plants can tolerate. However, it is well known that a higher CO_2 concentration in the air increases the thermal conditions in which the photosynthetic activity of the plants takes place, especially when humidity is available (Berry and Björkman, 1980). This should be the case in our experiments, where the CO_2 concentration was kept constantly above 1000 ppm and drought conditions avoided. As a matter of fact, it was consistently observed that vegetative growth took place inside the closed greenhouse at 35ºC and even higher temperatures. However, 35ºC is also generally considered amongst agronomist in Almería as the temperature above which the flowers of green beans start fading, a fact that was indeed observed in our experiments. Therefore, a first level of concern was established at that limit for defining the period when C4 heat-tolerant plants should be grown. A further level at 40ºC was considered to be a better representative of the limiting temperature in our case (as this has not been proved or evaluated yet, it was used only as a reference for evaluating the cooling performance).

The goal was then to shorten the period when the temperature systematically exceeded 35ºC and to avoid the occurrence of those peaks outside the warm season. During the evaluation of the prototype we proved that this could be achieved with the help of an adequate whitening of the greenhouse cover. While this is a standard practice with open greenhouses in the area, sometimes since February, it is an unwanted measure in the closed greenhouse. To take full advantage of the enhanced yield resulting from the increased CO_2 concentration, radiation should not be decreased. With an improved operation of the prototype, we have reduced progressively the necessity of shading. The main target was the de-loading of the heat during the night.

The passive cooling system operates on the basis that the heat stored during the day is released back into the greenhouse during the night. The same heat exchanger is used, and a water sprinkling is applied on its surface to enhance the heat release with the subsequent evaporation process. This constitutes a system to treat low quality water, as the humidity is further condensed on the cover of the greenhouse. It is not, however, the most efficient mechanism in terms of releasing the heat, as the exchanger is contained inside the thermally isolated tower. As a result, the lowest temperature reached by the storage with this operation is higher than the ambient temperature outside the greenhouse (Fig. 1).

In 2007, an additional system was tried between May 8th and September 13th. Leaving aside the possibility of water treatment, the hot water of the storage (20 m^3) was exchanged at the end of the day with cool water from a much larger storage (1000 m^3) used for irrigation of the whole Experimental Station. This source of cooling was still a few degrees higher than the ambient temperature, but the resulting effect was positive.

Fig. 2 shows the fraction of the daytime that the temperature inside the greenhouse exceeded 35ºC and 40ºC. If the high peaks around March 2006 are not taken into consideration (the leaf area index was still very small for sufficient evaporation), the thermal regime during both years was not drastically different. Regarding the level of shading, however, significant differences were evident. In 2007, shading only started at the end of April, and in a very soft way (30% reduction of transmission). Intense shading (between 60 and 70% reduction, which is the standard of the area) was only required from the end of July until the end of August. In 2006, not only the soft shading was employed for longer period of time, also the intense shading was kept during two months. It should have been more time, but in July-August a higher thermal regime was allowed because the crop was okra, which resists high temperatures. In short, during 2007 the improved thermal de-loading maintained the required thermal regime with much better light conditions.

Fig. 1 shows that there is still room for improvement with the concept of passive cooling, as the average ambient temperatures of the night were still below the cooling temperature used in the best case. A heat de-loading system which radiates the heat from the storage to outside the greenhouse during the night in the warm season would allow lowering the cooling temperature even closer to the ambient.

Cover material

The condensation that takes place constantly on the inner side of the cover is another important issue observed in the prototype. In order to avoid reduction of light transmission a good anti-fog material is essential. Moreover, for the collection of the condensate it is required that it takes place in a laminar way, so that it can slide to the recovery canals. Commercial anti-fog plastics are based in tenso-active additives incorporated in the formulation of the plastic. Unfortunately, these additives are soluble in the water and end up migrating after a certain time. In our experiments the duration of the anti-fog properties never exceeded one year. The best material was shown to be the five-layer plastic, most likely because of the larger amount of layers with additive. However, even in this case more than 50% of the total surface of the plastic totally lost its anti-fog properties after one year of operation. Fig. 3 illustrates the problem. The areas where the additive was dissipated are less transparent, as the water droplets decrease more than 50% its transmission.

As anti-fog plastic based on the usual tenso-active additives have a limitation, further alternatives should be considered. One is to create the anti-fog effect with physical more than chemical actuations. These techniques are still under investigation. Other cover materials based on different polymers with anti-drip properties could perform better. This could be the case of the ethylene tetrafluoroethyle (ETFE). Its anti-drip capacity allegedly lasts 10 years, but it has not been evaluated yet under the high demanding circumstances of closed greenhouses. ETFE poses a further advantage with its long durability. The optimum performance of the closed greenhouse requires continuous cultivation in order to guarantee high evaporative rates, so inter-planting with overlapping growing cycles is required to maintain a continuously high leaf area index. However, the standard polyethylene or EVA covers need to be replaced after 2 or 3 years due to their degradation by UV radiation. This interrupts the continuity of the inter-planting, so a long-lived cover would be more suitable.

CONCLUSIONS

The evaluation of the Watergy prototype showed the feasibility of a low energy consuming closed greenhouse for semi-arid climates. The closed greenhouse has guaranteed plant productivity during the whole year, avoiding the use of pesticides and closing the water cycle. Yield and water productivity achieved in the first trials were acceptable. There is still room for improvement with cultivars and agronomic management suited for the conditions of closed greenhouses. Also, climatic conditions can be further optimized.

In order to maintain adequate thermal levels inside the closed greenhouse with the passive cooling system, shading of the cover is required, as is the case with open greenhouses, incidentally. The period of application of whitening can be reduced if the original procedure of using all the energy stored during the day for water treatment releasing the heat back into the greenhouse at night for further water processing is modified during the warm season. During this period, thermal exchange with the outside air can cool the heat storage more during the night and therefore allow a better cooling capacity for the next day. Future designs of closed greenhouse following the lines of the passive cooling system used in the Watergy prototype should consider an additional night-sky radiation system to release the heat during the warm season.

The anti-fog property of the cover material proved so far to be an insurmountable problem. The durability of the standard anti-drip plastic materials is not enough for a continuous operation longer than two years. This impels the consideration of alternative materials and greenhouse shapes for further closed greenhouses. Finding a light plastic cover with the right properties is a challenge. A good candidate, which would definitely eliminate the changing of the cover, could be ETFE, but it is a very expensive material and its anti-drip quality is still to be evaluated in closed greenhouses.

Literature Cited

Buchholz, M., Jochum, P., Zaragoza, G. and Pérez-Parra, J. 2005. Concept for water, heat and food supply from a closed greenhouse – The Watergy project. Acta Hort. 691:509-516.

Buchholz, M., Buchholz, R., Jochum, P., Zaragoza, G. and Pérez-Parra, J. 2006. Temperature and Humidity Control in the Watergy Greenhouse. Acta Hort. 719:401-408.

Buendía D., Zaragoza, G. Gázquez J.C. and Pérez-Parra, J. 2007. Resultados del cultivo en diferentes estaciones dentro del invernadero cerrado Watergy. Proc. XI Congreso Nacional de Ciencias Hortícolas: Agriculturas Minoritarias. Albacete, Spain 24-27 April.

Zaragoza, G., Buchholz, M., Jochum, P. and Pérez-Parra, J. 2007. Watergy Project: Towards a rational use of water in greenhouse agriculture and sustainable architecture. Desalination 211: 296-303.

Zaragoza, G., Buendía, D., Meca, D., Pérez-Parra, J. and Buchholz, M. 2008. Experiences in Cultivation Inside the Watergy Prototype of a Closed Greenhouse for Semi-arid Regions. Acta Hort., in press.

Berry, J.A. and Björkman, O. 1980. Annu. Rev. Plant Physiol. 31:491-543.

<u>Figures</u>

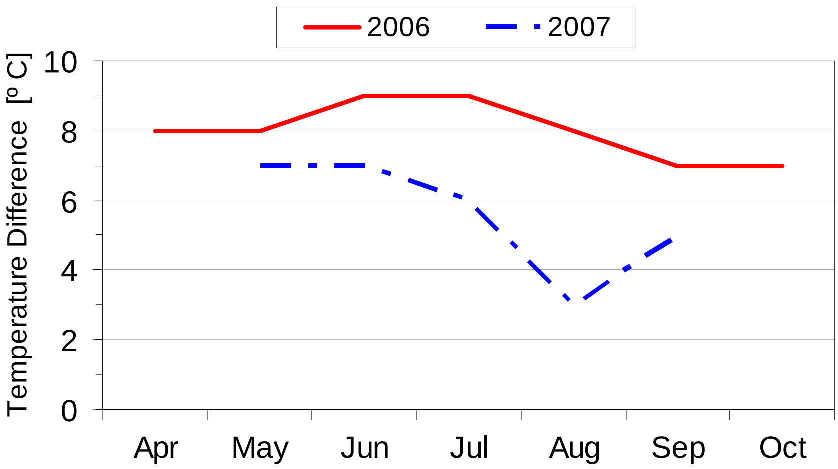

Fig. 1. Difference between the minimum temperature of the storage at the beginning of the day (start of the cooling period) and the average outside night time temperature.

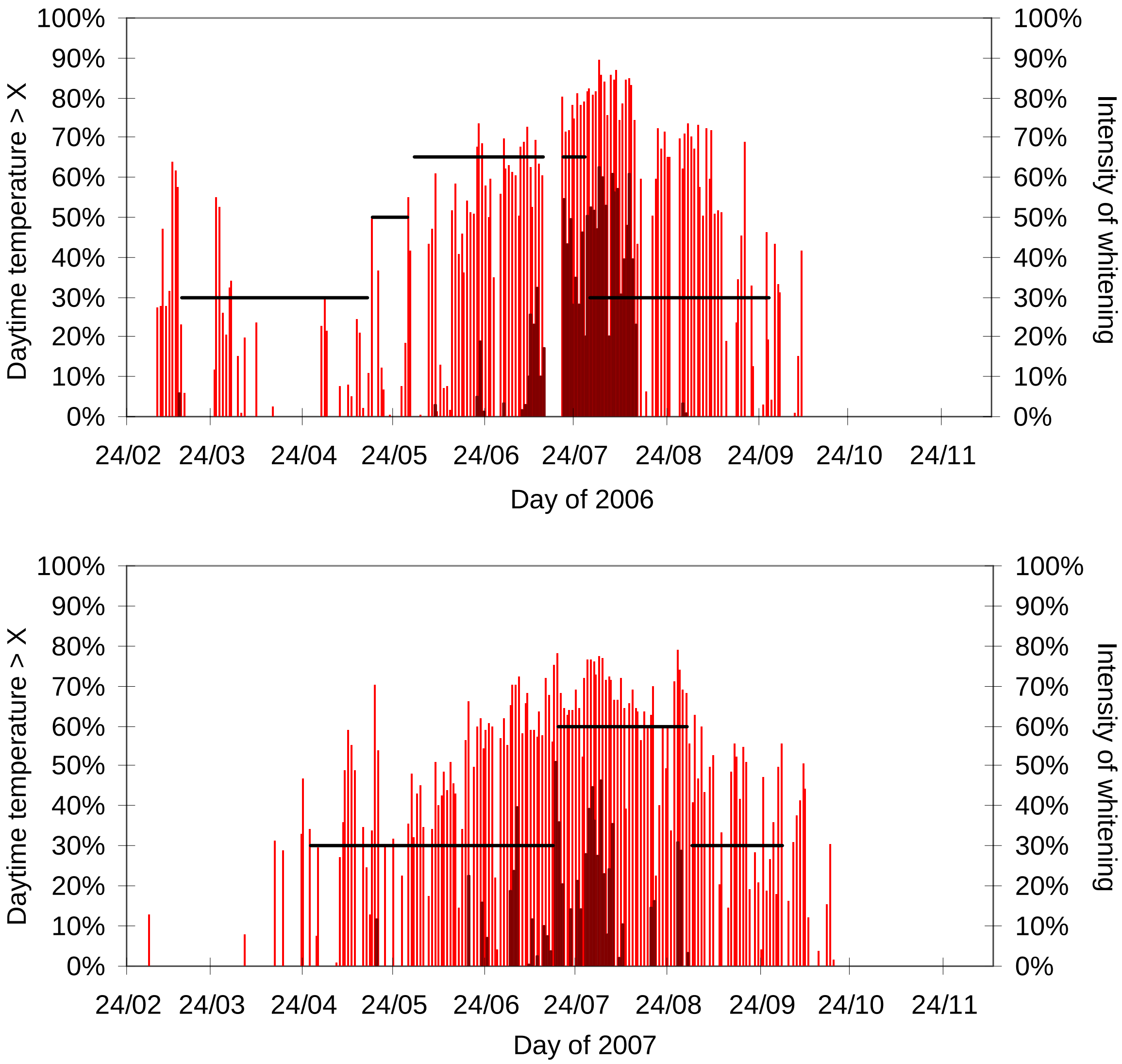

Fig. 2. Thermal levels of the closed greenhouse during two consecutive years. Vertical lines indicate the fraction of the daytime that the greenhouse temperature (5 minutes average) is above 35ºC (thin lines) or above 40ºC (darker areas). Horizontal black solid line indicates the intensity of whitening, expressed as percentage reduction of the transmission of the cover.

Fig. 3. Left: Image of the 5-layer plastic cover showing some spots where the anti-fog additive has disappeared. Right: Detail of the 3-layer plastic with the anti-fog property completely gone.