Lessons Learned from Experiments with Semi-Closed Greenhouses

H.F. de Zwart
Wageningen UR Greenhouse Horticulture
Wageningen
The Netherlands

Keywords: sustainable greenhouses, cooling, energy consumption, semi closed greenhouse

Abstract

In the past decade, experiments and a large number of model studies with closed and semi-closed greenhouses have been carried out. Technical, horticultural and engineering problems were solved and high production levels were achieved. Due to the capture of condensate and the reduced air exchange, water and CO_2 demands can be reduced significantly. However, the investments for a semi-closed greenhouse are high. Moreover, the running costs can be high as well, especially in situations where seasonal heat storage is difficult. This paper gives an overview of the results obtained by several research institutes as published in international accessible literature and discusses the key parameters that affect the technical and economic viability of semi-closed greenhouses.

INTRODUCTION

Around the turnover of the century, a company Ecofys, based in Utrecht, the Netherlands, boosted the development of the closed greenhouse. By a smart coupling of the heat demand in winter with the cooling demand in summer, by means of using aquifers as a heat storage medium, their design promised an affordable way to increase horticultural production and yet at the same time a decrease of energy consumption (Opdam, 2005). The most important novelty in their approach was to focus on storing chilled water in winter instead of storing heated water in summer. Until that time, cooled greenhouses have been mentioned as an option, but calculated to be too expensive (van de Braak, 1995). In the approach of Ecofys, heating the greenhouse with a heat pump in winter resulted in a certain amount of cold water which could be used for cooling in summer. Seasonal storage of cold water at temperatures around 8°C in deep subsoil aquifers, which is some 3 degrees below the natural deep soil temperature overcomes the energylosses which are subject to storing the reject heat from a chiller when providing cooling capacity in summer. In fact, the new approach gives cooling power as a beneficial waste product of heating a greenhouse in winter by means of a heat pump. However, the results of the Ecofys concept showed that the amount of cold water produced in winter by a 1 ha greenhouse in mild climate conditions provides the cooling capacity for only 1/3 ha of closed greenhouses. So, speaking of closed greenhouses in the Ecofys concept means that 1 ha of closed greenhouses is accompanied by 2 ha of ordinary, non-closed greenhouses.

Since cooling in the Ecofys concept is based on the waste product of heating in winter, the sustainability issue relates only to situations where the alternative heating technology has a serious energy demand for heating (say 600 MJ/m² per year or more). In regions with a very low heat demand, a (semi-)closed greenhouse will increase the energy demand, but might still be interesting from economical point of view.

The other consequence of the fact that cooling in the Ecofys concept runs on the waste product of heating is that a better insulated greenhouse, or a milder climate reduces the potentials of cooling. This reduction can be expressed in terms of a diminished surface ratio between the closed and the non-closed greenhouse, or in a stronger limitation of the maximal cooling power, which results in a semi-closed greenhouse. Obviously, in this article, a closed greenhouse refers to a situation where the cooling power is (almost) always enough to keep the vents closed, whereas a semi-closed greenhouse refers to a cooling strategy where a limited cooling power is used to provide some cooling during strategically smart periods.

One can also think of a closed or semi-closed greenhouse without considerations about whether or not the heat extracted can be reused for heating. In this approach, heat extracted from the greenhouse is removed to the outside air directly or with a small time lag (Novarbo, 2011). In these cases the benefits of the system are predominantly the savings on CO_2 and sometimes an improved climate by a lowering of greenhouse air temperature compared to a situation without cooling. Of course savings on CO_2 can only be realised in case the greenhouse is operated at an elevated concentration. For greenhouses that do not use CO_2-dosage, a decreased ventilation rate is actually a disadvantage since the replenishment of CO_2 inside the greenhouse from outside air will drop.

This article is an attempt to present an overview of the most important lessons that can be learned from a decade of experience, experiments and modelling on (semi-)closed greenhouses.

PROJECTS AROUND THE WORLD

When searching horticultural literature on the keyword 'greenhouse cooling', almost all texts found refers to cooling greenhouses by means of natural or forced ventilation. Articles handle about ventilation opening, the effect of insect nettings, fan-and-pad cooling, the contribution of the evaporation of the plant in cooling etc. Indeed, mechanical cooling of greenhouses is rare. Some articles state that mechanical cooling by refrigeration systems is feasible for special categories of crops (Fang, 1995). Worldwide it is quite common to cool a high value crop like Phalaenopsis.

The keywords 'closed greenhouse' and 'confined greenhouse' result in more suitable elaborations on the subject of this paper. A lot of work originates from the Netherlands (Opdam, 2005; de Zwart, 2011) and from the United States (Yildiz, 2006). Also French (Grisey, 2011) and German institutes (Buchholz, 2005; Meyer, 2011) report on closed greenhouses.

In all articles there is a tendency towards the semi-closed greenhouse. Where research was most of the time started with the objective of a full insulation of the greenhouse from the environment (except for the sunlight), the final recommendation was to allow for a strategic mixture of mechanical cooling and cooling with outside air. This recommendation is based on the fact that investments and running costs for a completely closed greenhouse are high compared to the revenues.

Only a few of the articles are based on actual measurements and where the results are based on measurements there is hardly ever a comparison with a representative non-closed greenhouse. Exceptions are the work of Qian (2011), which focuses on the effect of different cooling capacities and on-going work of Grisey (2011) where comparisons are made between a semi-closed and a standard greenhouse. These comparative experiments show the broad lines of the effects of greenhouse cooling in terms of energy and plant reaction, but since the impact of these effects are very much determined by local circumstances, the final judgement on the potentials predominantly have to be based on model computations. The next section briefly stated the topics that have to be addressed in these computations.

KEY ISSUES FOR (SEMI-) CLOSED GREENHOUSES

Literature shows a large number of aspects around the (semi-)closed greenhouses and most articles focus on particular details (temperature gradients, energy balance, storage issues etc.). The text below summarizes the state-of-the-art for the five most important issues.

The Horticultural Benefit Comes from Elevated CO_2-Concentrations

For some specific ornamental plants and cut flowers, greenhouse cooling to low temperatures (say 17°C) provides the major benefits that justifies the costs associated with cooling. For the major vegetable crops however, it is not the lowering of greenhouse air temperature which provides the extra production value. At a limited CO_2 dosing capacity (say 100 to 200 kg/(ha hr)), an increased cooling capacity yields a higher CO_2-concentration, especially on a bright sunny day. This appears from practical measurements and model computations (Qian et al., 2011).

The consequence of this fact is that the costs and availability of CO_2 for a particular greenhouse strongly affects the perspective of a semi-closed greenhouse. Where the reference, non-cooled greenhouse can supply large amounts of CO_2, *f.i.* from the exhaust gases of a combined heat and power engine that runs during daytime for electricity production for the public grid, the effect of cooling a greenhouse in terms of extra production will be diminished.

An interesting peculiarity is that greenhouses with cooling surprisingly enough tend to have higher average temperatures than non-closed greenhouses. This is predominantly because a higher average temperature is required to keep crop development in pace with the higher photosynthetic activity, due to the elevated CO_2-concentration. This is a nice coincidence since cooling becomes cheaper as the air to be cooled has a higher temperature (de Zwart, 2008).

Mechanical Dehumidification Gives Less Cooling Potentials

The evaporation of a canopy brings large amounts of vapour into the greenhouse air. To prohibit too high a humidity, greenhouses have to be dehumidified. In moderate climates, the (absolute) outside air humidities are normally substantially lower than the humidity of the greenhouse air. So, air exchange between inside and outside the greenhouse will almost always result in dehumidification. Therefore, as soon as an ordinary greenhouse opens its vents to avoid overheating, the humidity in the greenhouse hardly ever exceeds humidity thresholds. About the same holds for (semi-)closed greenhouses; as soon as the greenhouse has to be cooled, the humidity won't reach high levels due to condensation on the cold surfaces of the coolers. However, during cold periods, ventilation is undesirable to extract moisture because with the air exchange, sensible heat is lost as well. This makes that a substantial amount of the heating demand is associated with humidity control.

Due to this fact, the original concept for the closed greenhouse applied air treatment units with two heat exchanger segments. In cooling mode both heat exchangers are fed with cold water, but in winter, when dehumidification and heating are required simultaneously, the first exchanger can be fed with cold water and the second with warm water. Thus moisture condensates at the first segment whereas the second heat exchanger reheats the air and to compensate the sensible heat loss at the first segment and to provide heating for the greenhouse. With this 'mechanical dehumidification', sensible and latent heat loss to the environment is avoided leading to a lower heat demand of the greenhouse. However, for a semi-closed greenhouse, the savings on energy consumption are in the favour of a reduced amount of energy extracted from the aquifer and hardly in favour of a reduced electricity consumption. The latter is the most expensive form of energy in a closed greenhouse operation. But what's more, when closing the greenhouse during the summer is the major objective, this 'mechanical dehumidification' diminishes the cooling potential because less energy extraction from the aquifer in winter means less cooling water in summer.

Energy Saving Means Modest Cooling and Seasonal Storage

Greenhouses that consume a substantial amount of heat are located at northern latitudes, which means that the majority of heat is applied in winter and the majority of heat excess (ventilation of the greenhouse) takes place in summer. Energy saving in a semi-closed greenhouse essentially comes from the fact that summertime heat excesses are used for heating purposes in winter. This means that energy saving with a semi-closed greenhouse requires seasonal storage. Lee et al. (2009) reported about energy savings with intraday and inter-day storage of respectively 10 to 12%, whereas the energy savings by using seasonal storage can reach savings of 30% (Opdam, 2005) but 40% is reachable as well.

The fact that the energy saving sticks to values well below 50% is not caused by a lack of summertime heat excess. The amounts of energy surpluses that have to be removed from the greenhouse to avoid overheating have typical values of 2000 MJ per m² per year for northern latitudes, whereas heating demands are typically a factor 2 smaller. The reason that savings are limited despite the abundant surplus is that there is electricity needed to run pumps and ventilators and a substantial amount of electricity to run a heat pump that bridges the temperature gap between cooling water temperatures (around 10°C) and heating water temperatures (around 35 to 55°C). Attempts have been made to avoid the heat pump by using heat exchangers that work at very small temperature differences and accepting greenhouse temperatures uncontrolled between 17 and 27°C, which could lead to energy saving up to 80% or so. However, this would require a very large and expensive amount of heat exchanging surface in the coolers and heaters and also the wide uncontrolled range is adversely for high quality horticultural production (Bakker, 2006).

Giving a yearly heat demand of 1000 MJ/(m² year) for a well-insulated greenhouse in a moderate climate and a heat pump that provides this heat with a coefficient of performance of 4, the heat extracted from the seasonal storage system is around 1000 * (4-1)/4 = 750 MJ/(m² year). Now, when considering that a greenhouse tends to become overheated in about 2000 per year, the average cooling capacity that provides this 750 MJ is $750 \cdot 10^6/2000/3600 \approx 100$ W/m². This 100 W/m² is far smaller than the heating loads on a greenhouse when exposed to 900 W/m² of outside radiation, which shows that gathering the heat for regeneration of the seasonal storage system requires only modest cooling capacities.

An exception of this reasoning is when a small fraction of a greenhouse complex is dedicated to energy harvesting for a much larger fraction that uses the heat harvested. In this case, the small cooled fraction has a much higher cooling capacity, but the average capacity of the entire complex won't be very different from this 100 W/m².

The cooling capacities will drop to even lower values when greenhouses are better insulated or in case the electricity for the heat pump is generated by an on-site combined heat and power system. The latter is the case in common large scale greenhouse operation in the Netherlands.

Horizontal and Vertical Temperature Gradients

Literature on (semi-)closed greenhouses shows a variety of devices that serve the heating and cooling demand. They have all in common that attempts are made to limit the temperature differences that drive the heat exchange between greenhouse air and the heating and cooling device. That's why the majority of heating and cooling systems are based on forced ventilation through air treatment units or fan coils. There are systems where cooling is served overhead the canopy and systems where cold air is blown into the greenhouse from below the gutters. There are systems with decentralized fan coil units, each serving some 80 m² of greenhouse, and there are systems with large air treatment units that cool, dehumidify or heat the greenhouse air and distribute the air over 200 to 400 m² by means of foil ducts. All experiences show that horizontal and vertical temperature gradients tend to become unacceptably large. When using centralized air treatment units with air ducts for heating, structural temperature differences in the crop may reach 2°C along the ducts (de Zwart, 2011) and when these ducts are used to cool from below the gutters, vertical gradients can reach up to 6°C (Qian, 2011). Moreover, the low temperatures in the bottom region of the crop slows down the ripening of fruits and is likely to result in unfavourable low temperatures in the root zone. Decentralized fan coils that heat and cool the air from above the crop give a better homogeneity, especially on the longer term. Hour to hour variations show differences around 2°C as well, but since the warm and cold spots 'walk around' the greenhouse surface, on the longer term (e.g. one week) structural temperature differences can drop below 1°C. However, overhead fan coils require quite a high greenhouse to provide enough 'mixing space'. Also there is an interception of light, which is generally detrimental. Moreover, for heating, the heat losses are higher when using overhead fan coils.

Due to the difficulties concerning homogeneity and in addition the electricity consumption of air circulation, for heating the use of common heating pipes can be a good alternative. The overall effect on high quality energy consumption (the heat pump serving ordinary heating tubes runs on a less optimal coefficient of performance) is than limited to something like 5 kWh/m² year (de Zwart, 2011). One way to combine the good horizontal homogeneity of heating pipes with still a low heating system supply temperature is a doubling of the number of heating pipes per span.

The electricity consumption of ventilators while preserving horizontal homogeneity during cooling can be lowered when cooling is based on natural convection as well. The ZINEG-project in Germany uses three overhead finned pipes per 6.40 m span to yield 150 W/m² cooling energy.

The Semi-Closed Greenhouse Is in Competition with Other Reject Heat Sources

As stated by Yildiz (2006), the greenhouse with heat pump and extraction of sustainable heat from the heat excesses in the greenhouse has an economical advantage over a greenhouse heated by a gas or oil fired boiler. However, there are other heat sources for greenhouses as well. In The Netherlands, the reject heat of Combined Heat and Power is a very tough competitor. The easy access to natural gas, the relatively cheap gas and the good infrastructure for selling of electricity to the public grid give Dutch growers good possibilities for electricity trading. Growers with greenhouses of 4 up to 20 ha operate CHP-engines with an electric power of 500 kW per ha (so 2 to 10 MW of electric power). These substantial power range enables them to play an important role in the market for short term balancing of electricity production and electricity demand. Due to the revenues from this electricity trading the reject heat of the CHP-engine can be considered as almost free heat. Compared to this almost free heat, heat produced by a heat pump, requiring high quality energy, is more expensive which makes that in a Dutch greenhouse with both a large CHP and a heat pump, the number of hours where the heat pump can do its job is quite limited. This makes that investments in the heat pump and seasonal storage cannot be earned back.

It is clear that the reasoning above is very much dependent on the difference between the production costs and the selling price for electricity. This difference is referred to as the spark spread. In the Netherlands, the spark spread shows a decreasing tendency. Based on the current spark spread, a semi-closed greenhouse is near to viability but it is difficult to predict whether this low spark spread will persist.

CONCLUSION

Literature shows that many institutes all over the world have built up facts and experiences with the operation of closed greenhouses. The major conclusion is that semi-closed greenhouses, meaning a greenhouse with a quite limited cooling power, is to be preferred over a completely closed greenhouse. For a semi-closed greenhouse, the revenues come from savings in energy consumption, rather than elevated production levels.

The technology around semi closed greenhouses has reached maturity. In literature the major pitfalls, do's en don'ts can be found. However, the availability of aquifers for the seasonal storage of heat is an essential necessity, which limits the area where these types of greenhouses will be able to flourish. Also, since the drilling costs for aquifers have an important fixed cost component, a feasible semi-closed greenhouse starts at a minimum surface of at least 1 ha.

The economic viability is very much dependent on the energy price and, of course, also on competitive techniques and energy sources. Wherever there is cheap reject heat, the high investments for the seasonal storage, the heat pump and the coolers hamper the viability of the semi-closed greenhouse. In the Netherlands, currently the widespread use of CHP acts as a provider for cheap reject heat, which explains why the semi-closed greenhouse is currently not expanding.

ACKNOWLEDGEMENTS

Most of the projects on climate and energy research employed by Wageningen UR Greenhouse Horticulture are funded by the Product Board of Horticulture in the Netherlands and the Ministry of Economic affairs, Agriculture and Innovation.

Literature Cited

Bakker, J.C., de Zwart, H.F. and Campen, J.B. 2006. Greenhouse cooling and heat recovery using fine wire heat exchangers in a closed pot plant greenhouse: design of an energy producing greenhouse. Acta Hort. 719:263-270.

Braak, N.J. van de 1995. Greenhouse construction and equipment. In: J.C. Bakker, G.P.A. Bot, H. Challa and N.J. van de Braak (eds.), Ch. 6 Greenhouse Climate Control.

Buchholz, M., Jochum, P. and Zaragoza, G. 2005. Concept for water, heat and food supply from a closed greenhouse - the watergy project. Acta Hort. 691:509-516.

Fang, W. 1995. Greenhouse cooling in subtropical regions. Acta Hort. 399:37-48.

Grisey, A., Grasselly, D., Rosso, L., D'Amaral, F. and Melamedoff, S. 2011. Using heat exchangers to cool and heat a closed tomato greenhouse: application in the south of France. Acta Hort. 893:405-411.

Lee, W.F., Ling, P.P. and Keener, H.M. 2009. Cooling capacity assessment of semi-closed greenhouses, 2009 ASABE Annual International Meeting.

Meyer, J. 2011. Extremely insulated greenhouse concept with non-fossil fuel heating system. Acta Hort. 893:201-208.

Novarbo, Biolan. 2011. Finnish company selling a cooling system based on a curtain of cold water droplets. Website in 2011 was: http://www.novarbo.fi/image/esitteet/Novarbo_Greenhouse_EN.pdf

Opdam, J.J.G., Schoonderbeek, G.G., Heller, E.M.B. and de Gelder, A. 2005. Closed greenhouse: a starting point for sustainable entrepreneurship in horticulture. Acta Hort. 691:517-524.

Qian, T., Dieleman, J.A., Elings, A., De Gelder, A., Marcelis, L.F.M. and Van Kooten, O. 2011. Comparison of climate and production in closed, semi-closed and open greenhouses. Acta Hort. 893:807-814.

Yildiz, I. and Stombaugh, D.P. 2006. Simulated performances of a heat pump system for energy and water conservation in open and confined greenhouse systems. Acta Hort. 718:341-350.

Zwart, H.F. de, 2011. The Sunergy greenhouse - one year of measurements in a next generation greenhouse. Acta Hort. 893:351-358.

Zwart, H.F. de and Kempkes, F.L.K. 2008. Characterizing of cooling equipment for closed greenhouses. Acta Hort. 801:409-416.