Greenhouse Engineering: New Technologies and Approaches

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Abstract

Firstly, this article discusses the greenhouse engineering situation in three geographic areas which are relevant in the field of protected cultivation: Northern Asia, The Netherlands and the Mediterranean. For each area, the prevailing greenhouse type and equipment is briefly described. Secondly, the main technological constraints are pointed out and finally the research directions are discussed. For all areas under consideration, attempts to design more efficient greenhouse systems are under way. In Northern Asia progress is being made towards the optimisation of greenhouses as a solar collector and to the development of new heating strategies. Important subjects addressed in The Netherlands are energy conservation and the replacement or alleviation of human labour by increasing mechanisation. In the Mediterranean there is growing interest in semi-closed greenhouses with CO_2 enrichment and control of excessive humidity. All geographic areas share the need of having an optimised climate control based on the crop response to the greenhouse environment. All areas also share the requirement of being respectful to the environment, therefore future greenhouses are expected to use engineering to produce with minimal or zero emissions.

INTRODUCTION

Greenhouse engineering is a broad concept that integrates subjects such as energy saving, cooling, automation and structural design. Since the technology and developments related to greenhouse engineering are copious, this paper concentrates on the analysis of three well establish production areas, such as Northern Asia, The Netherlands and the Mediterranean. Their different climatic, sociological and economical features provide a wide diversity of situations and an ample range of engineering problems and related solutions.

In spite of the adverse climate conditions (cold winters and hot summers), Northern Asia is the home of the largest area devoted to protected cultivation. Countries such as China, Japan and Korea play a relevant role in greenhouse horticulture and its associated engineering. Perhaps the most advanced and intensive technology can be found in The Netherlands. This is particularly true in topics such as labour automation and climate control. The Mediterranean basin benefits from mild winters and warm summers, thus requires soft, if any, heating technology and relatively cheap passive greenhouses with little climate control.

For each geographic area under consideration this article discusses the prevailing production system, the main technical constraints and the main directions followed by the greenhouse engineering research on each location.

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GREENHOUSE ENGINEERING IN NORTHERN ASIA

Prevailing Production Systems

Climate and geography are very diverse, which causes a high diversity of greenhouse crop productions in this region. Greenhouse structures, environmental control methods, crop production systems, agricultural materials, and crop management methods are different among the countries from southern to northern parts of Asia, due to their differences in climate and plant resource. For instance, Korea located in the northeast area has typically four seasons in a year while southern countries such as Vietnam and Thailand have two seasons.

As the greenhouse type is affected by regional climate, various types and management methods have been established. In southern parts, rain shelters with insect-proof screens are very popular due to their tropical climate and most of the greenhouses are unheated for crop production. Therefore efficient ventilation in rain shelters is one of the most interesting issues in these areas (Palada and Ali, 2007). In subtropical areas including Taiwan, cooling methods are intensively applied to overcome high temperature for production of high value-added crops like orchids. In the northern area, approximately 80% of protected horticultural areas in the world are run by China (71%), Korea (4.5%) and Japan (4.5%) (Lee et al., 2004). In China, a type of greenhouse named "solar greenhouse", which is similar to an uneven greenhouse, is very popular by enabling crop production with low investments and no heating (Chen, 2001). Many researchers have conducted work to standardise and improve this type of greenhouse.

Various types of greenhouses have been established in Korea and Japan, using plastic films and glass covers. For year-round production of horticultural crops, heating is required due to their typical climates. Heated greenhouses in Korea occupy around 24% of total greenhouse areas (52 000 ha) and that in Japan is around 43% of total 53 000 ha (Son, 2008). When needed, evaporative cooling is also used in summer for efficient use of greenhouses. Focusing on greenhouse crop production in the northeast area, there are two trends: sub-optimal environment producing medium-quality products with low investment and optimal environment producing high-quality products with high investments. The ratio of heated to unheated greenhouses will be a good index to explain the strategy in management of greenhouses.

Regional Constraints in Greenhouse Production in Northeast Areas

1. The Need for Efficient Greenhouse Heating in Winter. Energy saving is the most important in greenhouse crop production. Unlike tropical and subtropical areas, night temperature from late fall to early spring goes down to a very low level and thus heating is required for maintaining indoor temperature over adequate level. To reduce the energy for heating, many research approaches were conducted with development of greenhouse structures, application of better isolated covering materials, improvement of environmental control methods, positive use of natural and alternative energies, and so on (Kang et al., 2007). The simplest method for energy-saving is to receive solar radiation as much as possible, keep the heat inside the walls, and prevent energy loss by using well-insulated coverings at night as conducted in "Solar greenhouse" (Chen, 2001). The performance of this greenhouse may be changeable depending on its size and the season. Application of optimum environment control always requires enough training and understanding of how to use it for its practical use. In case of commercial greenhouses, the automatic control system is often removed a few years after installation because it does not work properly. Although the use of natural and alternative energies is the most interesting topic, the possibility of using them is not always the same in different countries due to the required cost and technology.

2. The Need for Efficient Greenhouse Ventilation and Cooling in Summer. Ventilation is a basic action to control indoor temperature, humidity, and other toxic gases in the greenhouse. In summer, ventilation will be the best treatment for crop production without cooling (Handarto et al., 2006; Kim et al., 2008; Nam et al., 2007). Only small portions of the total plastic houses occupying 95% of the total greenhouses in Korea use evaporative cooling and the rest of greenhouses depend on ventilation for crop production even in summer. For efficient ventilation, general analysis on temperature distribution and the effect of location of fans in the greenhouse were conducted (Lee et al., 2005; Yu, 2008). A question to be answered is whether the information developed for research-scale greenhouses is valid for commercial large-scale greenhouses.

Regarding cooling, evaporative cooling efficiency is relatively low due to the high vapour pressure in summer, which is when cooling is required. As evaporative cooling increases relative humidity in the greenhouse, diseases may develop at lower efficiency under high vapour pressure. However, most farmers want to use greenhouses during the whole season.

3. The Need for Efficient Moisture Control System in Greenhouse. Root-zone environment is another aspect to be evaluated for crop production. Requirement of water in plants depends on environmental factors such as radiation, VPD (temperature and relative humidity). To improve yield and quality of crops, moisture control of the growing medium associated with environmental factors is needed. Most controllers control the moisture content with only moisture sensors not considering environmental data totally. The regions with drastic changes in environmental factors need more accurate moisture control.

4. The Need for Control Strategies for Industrialized Greenhouses. To meet the cost-benefit balance, the unit size of a greenhouse complex became expanded recently. Even though greenhouse control factors including environmental factors increase and control systems become more complicated, systemic monitoring and control are required. Compared to Japan, agricultural companies relating greenhouses in Korea are so small that they cannot keep supporting farmers continuously and stably. An environmental control system using accumulated cultivation data is required for stable, high-quality crop production in industrialized greenhouses.

Recent Tendencies in Greenhouse Engineering in Northern Asia

1. Energy-Saving Strategies. To reduce the energy loss from the greenhouses, improvement of greenhouse structure and thermal curtain is required and progressed. Highly-insulated curtains can prevent the heat transmission from the greenhouse. Due to high oil price, the use of natural energies such as solar energy and underground heat and the utilization of a by heat pump are important issues (Kang et al., 2007; Ryou et al., 2008). Heating load will be reduced by supplying the heats to the only space that needs suitable temperature for plant growth, like bench-heating (Son et al., 2007). A package strategy is also taken into account for efficient energy-saving.

2. Efficient Greenhouse Environmental Control. For better distribution of indoor temperature in greenhouse, location and number of fans are reviewed (Yu, 2008). The height of greenhouses also becomes higher than normal for improving environmental conditions as well as productivity. However, energy loss and greenhouse materials increase at the same time. Temperature control with time during the day and night is conducted in some greenhouses, and integrated solar radiation can change the set points of temperature.

3. Development of Crop Production Systems. Standardization of greenhouse unit size, culture system, and information technology are progressed for efficient crop management. To increase productivity all year-round utilization of greenhouse is required through planned and stable production. Labour-saving technologies with automation and easy growing systems for aged farmers are reviewed. Soilless culture systems including various moisture control methods have been introduced (Oh et al., 2007).

4. Positive Strategy for Large-Scale Industrialized Greenhouses. For high-quality products, optimal environment with high investments are suggested and the scale of greenhouses becomes larger to meet the cost-benefit balance. Integrated control systems, environmental-sound technologies, and energy-saving strategies by using solar radiation, underground heat, and bio-energy from waste treatment are taken into account.

GREENHOUSE ENGINEERING IN THE NETHERLANDS

Throughout the decades, greenhouse crop production has become a very successful branch of the Dutch agricultural production. Nowadays, greenhouse crop production in The Netherlands yields 40% of the total agricultural production value on only 0.5% of the available acreage that can be used for agricultural production. High production levels are realized with high levels of technology. However, technology comes at a price and the investment costs are consequently high as well.

To face international competition, the Dutch greenhouse industry continuously seeks ways to improve the economic efficiency of the production process. This is achieved in two ways; by increasing the economic yield or through the reduction of costs.

Increasing the productivity of the crops grown, production of specialties for specific markets, high quality products as well as product certification are examples of ways used to improve the economic yield. There is also a strong focus on consumer driven production (just in time, just enough and just the right quality).

But cutting costs is equally important. Scale enlargement is one of the trends in that direction. Whilst in the 1970s the average size of a greenhouse production facility was 0.5 ha, currently, the average size amounts to 1.5 ha and facilities of 5 ha and more are common today. Currently, with 27, 18 and 18%, labour costs, energy costs and capital costs, rank number 1, 2 and 3 on the list of operational costs in Dutch greenhouse crop production (De Bont and Van der Knijff, 2007). Clearly, labour and energy use rank high on the list of priorities when it comes to systems innovations. Besides rising labour costs, the availability of sufficiently trained staff and health issues are a source of concern for Dutch growers. Cutting the energy consumption also ranks high on the list of priorities of the Dutch government since the greenhouse industry accounts for 10% of the total Dutch consumption of natural gas. Therefore, the government and greenhouse industry have agreed on improving the energy efficiency of crop production to a level of 35% compared with the reference year 1980. The next focus lies on realizing climate neutral greenhouse crop production by the year 2020. Target is also to reduce the CO_2-emission to 45% of levels in 1990.

Evidently, the trends described above have had their impact on greenhouse engineering and below research directions tackling these challenges are shortly discussed.

Research Directions in The Netherlands

1. Energy Efficiency, Energy Consumption or Energy Production. Improving the energy efficiency of greenhouse crop production has been a topic of research for many decades in The Netherlands. Focus lies on improving the insulation of greenhouse construction whilst maintaining high light transmission (e.g., Sonneveld and Swinkels, 2005), the development of energy neutral and semi-closed greenhouses (e.g., De Zwart and Kempkes, 2008; Ooster et al., 2008b), energy producing greenhouses (e.g., Sonneveld et al., 2008) and use of geothermal energy (e.g., Ooster et al., 2008c). These lines of research will continue. Additional topics for the future will be shared production and distribution of energy by clusters of companies and bio-fuel driven cogeneration. For a detailed description of ongoing research in this area refer to the companion paper of Dieleman and Hemming (2011).

2. Supplementary Lighting. In The Netherlands, supplementary lighting is a commonly accepted instrument to increase productivity and quality of greenhouse grown crops. Supplementary lighting is combined with cogeneration producing both electricity and heat using natural gas. Currently, supplementary lighting is installed in about 2000 ha of greenhouses (Heuvelink et al., 2006; Van Ieperen and Trouwborst, 2008). Commonly used light sources are High Pressure Sodium lamps. To reduce light pollution, since 2005 legislation requires light emission of greenhouses to be reduced with 95% during night time. This poses various technical research challenges. HPS lamps pose a considerable thermal load on the greenhouse system and screening to prevent light pollution, trivial as it sounds, is therefore not a generally applicable solution (Ooster et al., 2008a). Therefore, alternative ways of producing or distributing light are topics of research. Light-Emitting-

Diodes are considered a potentially feasible option. However, cost price, efficiency, power rating and emitted spectra are topics of ongoing technical and plant physiological research (Shimomachi et al., 2006; Ieperen and Trouwborst, 2008).

3. Efficiency, Alleviation or Replacement of Human Labour. To tackle the challenges in the field of labour (costs, availability, health issues) current research focuses on more effective layout of the company, proper or preferably optimized scheduling of labour and support, alleviation or even replacement of human labour by machines.

Dealing with above issues is a complex matter and the stakes are high. Complexity issues have to do with the inherent variability of the produce, uncertainty in the weather which makes production scheduling a difficult issue and last but not least uncertainty in the field of consumer demand.

Though based on estimates and calculations, currently, company layout, scheduling of labour and development, investment and implementation of mechanization are largely based on long-term experience, intuition and heuristics. Systematic and quantitative methods to analyse, simulate and optimize the production process and to support decisions in this field are hardly available and, for sure, not commonly used in Dutch horticultural practice. Then systems innovation becomes a bit of a gamble. Sometimes it may yield success and sometimes good ideas lead to bankruptcy of the companies involved, for reasons not understood. Interestingly enough, these issues have not received much attention in horticultural engineering research in the past years. Using instruments and paradigms from industrial systems engineering, in The Netherlands research is currently being focused on the development of systematic, preferably quantitative methods to analyse, design, simulate and optimize greenhouse crop production systems focused on company layout, scheduling in place and time of human labour as well as (potential) mechanization, taking into account product and information flows at company level. Examples of research in this field are described by Bechar et al. (2007), Eben-Chaime et al. (2008) and Van Henten and Kruize (2008). The latter compared stationary rose growing systems with recently adopted mobile growing systems for roses. Inspired by conveyor belts used in industry, using mobile growing systems a reduction in labour costs of 30% was expected, but in practice, these results were not achieved.

The above mentioned research will also support decisions in the direction of the feasibility conditions for replacing humans by machines. A review on the state-of-the-art in mechanization in protected cultivation revealed that mainly the first (seeding, grafting, cutting, potting, internal transport) and the final (sorting, packing) parts of the crop production process have been mechanized to a large extent (Van Henten et al., 2006). In those cases, position, shape, size and colour are quite clearly defined and industrial automation usually suffices. Crop maintenance and harvest are still very precarious treatments relying on human intelligence and effective and fast eye-hand coordination. Advanced robotics technologies are needed, but despite considerable research effort (e.g., Belforte et al., 2006; Yamamoto et al., 2008), commercial applications of robots are still very rare. Therefore, alleviating human labour with sensors, ambient intelligence or dedicated tools (Ota et al., 2006) might be good intermediate alternatives. Various options in these directions are discussed in the companion paper of Pekkeriet and Van Henten (2011).

4. Monitoring and Control of the Greenhouse Crop Production Process. With the growing scale of the greenhouse production facilities and the continuous focus on efficient production of high quality produce, process control, i.e., control of the aerial and root environment of the crop is a complex challenge. Process control has gone through a rapid development the past decades. Coming from manual control in the late forties, early fifties of the past century, today most greenhouses in The Netherlands are equipped with advanced process control systems for both aerial and root environment of the plants. Essentially, this trend shows that in greenhouse process control, gradually, the knowledge and experience of the grower is replaced by advanced control schemes to alleviate the task of the grower and to achieve the best decisions in the complex multi-variable decision environment considered. This trend will continue. Schemes to monitor and control the water and nutrient content in substrates have been extensively dealt with by Gieling (2001). Examples of advanced control schemes for the aerial environment of the crop, based on the optimal control paradigm, include De Graaf (2006), Van Oothegem (2007) and Speetjens (2008). Van Henten et al. (2006) demonstrated the potential of energy efficient control of production fluctuations in sweet pepper production. Practical application of such advanced schemes is, however, hampered by the fact that the process models these advanced control schemes rely on, have a limited predicting capability. Then feedback control schemes are needed (De Graaf, 2006; Van Ooteghem, 2007) and online parameter estimation techniques come to help, as demonstrated by Speetjens (2008). And last but not least, the growers have to understand and accept the strategies produced by such control schemes. Then collaborative learning approaches using real greenhouse data and simulations offer a route to make growers acquainted with alternative approaches to greenhouse climate management (Buwalda et al., 2008).

The past decade has also shown the advent of a broad range of sensors to monitor crop status. Supported with this information of the production process, the decision about alternative management strategies is largely left to the grower. To support growers in that direction requires interpretation of large sets of sensor data, data mining, time-series analysis and multi-variate statistics. Interesting other trends in the field of sensing include new sensing principles such as plant status monitoring based on measurement of emission of volatile organic compounds (Jansen et al., 2008, 2009), wireless sensor networks to unveil the heterogeneities in the production process (Van Tuijl et al., 2008), sensor accuracy as an important source of error in process control (Bontsema et al., 2008) and soft-sensor principles to assess for instance the ventilation rate of greenhouses and transpiration rate of crops (Bontsema et al., 2005, 2008) based on commonly available climate sensors and dynamic energy and mass balances.

GREENHOUSE ENGINEERING IN THE MEDITERRANEAN

Most of the “Mediterranean greenhouse agrosystem” has minimal climate control equipment, enabling the plants to produce an economical yield with low investments (Enoch, 1986; Castilla and Montero, 2008). The trend in the Mediterranean has been to adapt the plant to a suboptimal environment, in contrast to the requirement of optimizing the greenhouse environment for reaching the maximum crop potential yields (Castilla, 2002).

A number of comparative tests have been conducted in order to find the most profitable combination of greenhouse types and associated technology (Castilla and Hernandez, 2007). According to these studies, if properly designed, simple greenhouses can have similar light transmission and similar ventilation rates than more complex greenhouses. As a consequence, for vegetable production in areas with mild climate, properly designed passive greenhouses could reach a similar cost-benefit balance as industrial-type greenhouses with climate control equipment. This conclusion is valid for “regular” years, in which extreme temperatures, intense high humidity periods or severe virus attacks do not take place, but when one of these circumstances happens, the industrial greenhouse can modulate the unfavourable external conditions and offer more reliability to the grower. Perhaps the main advantage of applying technology in the sort of climates we are discussing is to add security and stability to the greenhouse operation, which, on its own, could increase profitability in the present market conditions (Montero et al., 2009).

For how long this suboptimal approach is affordable to the growers is a debatable issue, given that we are in a global market that only rewards dependable and steady deliveries of consistently high quality (Stanghellini et al., 2009). Innovations and incorporation of technology are no doubt needed. Nevertheless, short term predictions for the Mediterranean agrosystem aim at an evolution of the passive greenhouse based on sustainability principles such as the wiser use of natural resources (mainly solar radiation and wind driven ventilation). Perhaps a “good-tech” production model with moderate investments instead of a more ambitious “high-tech” high investment model is what is expected to happen in the Mediterranean.

Technological Constraints in Mediterranean-type Greenhouses

Among the technological limitations of existing greenhouses, three subjects that deserve special consideration are: excessive temperature during most part of the growing period, excessive humidity levels for the winter crops and lack of suitable controllers for warm climate areas.

1. The Need for Efficient Greenhouse Cooling. Latest research in greenhouse cooling highlights the role of natural ventilation as the main technique for controlling excessive temperature, and identifies CFD (Computational Fluid Dynamics) as a very powerful tool for the design of better ventilation systems. Since the early work of Okushima et al. (1989), CFD modelling has been widely used to predict not only ventilation rate but also the spatial distribution of relevant variables in the greenhouse climate. A recent review on ventilation modelling and internal air movement can be found in Boulard (2006) and Sase (2006), respectively.

Much has been learnt on greenhouse cooling and ventilation during the last years, but there is still a lack of information on important subjects such as the interaction between the crop and the greenhouse climate; good modelling of the main crop physiological processes has to be incorporated to CFD studies in order to improve the realism of CFD predictions.

2. Excessive Humidity in Plastic-Covered Greenhouses. Closed and semi-closed greenhouses are contemplated as a solution for greenhouse production in the Mediterranean (Buchholz et al., 2006). A number of advantages such as a more favourable night time temperature for the winter crops and considerable (up to 80%) water savings are expected from closed or semi-closed greenhouses. Also, closed and semi-closed greenhouses can benefit more from CO_2 enrichment (Stanghellini et al., 2009). But closing the greenhouse has two main problems, which are the difficulty of keeping the maximum temperature below detrimental levels and the development of condensation and dripping over the crops, with negative effects on light transmission (Pieters et al., 1997) and disease problems.

The issue of controlling excessive humidity in plastic-covered greenhouses is still unresolved, and the development of plastic greenhouses capable of managing humidity remains a challenge in greenhouse engineering.

3. Controllers for Warm Climate Areas. In those few Mediterranean greenhouses with climate control equipment, the control strategies are mainly empirical and try to reproduce the grower’s know how at using the actuators manually. The main problems associated with this sort of controllers are as follows:

- Most commercial systems contain a high number of heuristic rules and very often require the definition of more than a hundred parameters related to the climate trajectory and actuators performance.
- Climate variables set points tracking is not defined by taking into consideration the crop response to climate, which creates inefficiencies in the system performance.
- For warm climates there is a lack of knowledge and experience on how to control the combined use of cooling equipments, such as fogging systems, movable shading and ventilators operation.

A major reason for the slow incorporation of climate equipment in the Mediterranean is the lack of suitable and user friendly climate controllers.

Innovations and Tendencies in Greenhouse Engineering for the Mediterranean

1. New Greenhouse Structures with Improved Natural Ventilation. Kacira et al. (2004) conducted CFD simulations to investigate the effect of side vents in relation to the span number. Compared to roof ventilation only, when both side walls were fully open the ventilation rate increased strongly. Baeza (2007) studied the effect of greenhouse geometry on ventilation. Parameters such as roof slope, ventilator size, ratio of sidewall ventilation and greenhouse width and the comparison of windward ventilation to leeward ventilation were analysed. This author suggested to open the roof ventilators towards the wind (windward ventilation), to reduce the greenhouse width (no more than 50 m), to have a minimum roof slope of 30° and to increase the roof ventilators' size. Moreover, he stressed the importance of using deflectors to redirect the entering air towards the cropping area, a feature also suggested by Sase (1989) and Nielsen (2002).

For large-size greenhouses, leeward ventilation is normally preferred over windward ventilation to improve climate uniformity. Mistriotis et al. (1997) and Reichrath and Davies (2001) described the existence of a reverse flow in the windward part of the greenhouse and of a dead zone with low velocity at approximately 60% of the total greenhouse length. Reichrath and Davies (2001) did their simulations for a large 60 spans Venlo-type greenhouse. Attempts are being made to reduce these dead areas with low air speed and high temperature. Some recent and unpublished simulations show that under wind driven ventilation it may be convenient to close some of the roof ventilators to create a cyclic entrance and exit of air with better air mixing within the crop zone. Other innovations on greenhouse ventilation are currently being developed (Montero et al., 2008).

2. Semi-Closed Greenhouses with CO_2 Enrichment. During sunny, chilly days the ventilation of the greenhouse implies a trade-off between ensuring inflow of carbon dioxide to prevent CO_2 depletion and adequate temperature within the house. It has been estimated that the loss in production due to CO_2 depletion in Southern Spain is around 8%. This decrease in yield can be compensated by increasing the air temperature by 1.6°C (Stanguellini and Kempkes, 2008). Semi-closed greenhouses are able to maintain minimum temperatures usually 3-4°C higher than outside (Buchholz et al., 2006). Additionally, semi-closed greenhouses can strongly benefit from CO_2 enrichment by keeping ventilation as little as the control of humidity would allow.

The problem of excessive humidity is more severe in passive, unheated greenhouses because it is not possible to heat and ventilate simultaneously as it is done in zones with temperate climate. The problem has been aggravated by the incorporation of insect-proof screens that strongly limit air exchange and humidity extraction. Several attempts have been made to dehumidify the greenhouse (for instance, Kim et al., 2008; Yıldız and Stombaugh, 2006). While most of these systems worked efficiently, their investment and operational costs were far from the technology currently used around the Mediterranean.

Another approach to solve the humidity problem is by changing the roof design. A sloped roof can make condensation run off if the plastic film is properly tensioned. Later, the condensate can be collected in the gutter as it is done in Venlo-type greenhouses. Some new structures that incorporate this feature are being erected in Almeria (Southern Spain) as part of a demonstration project on new technologies (Fundacion Cajamar-CTA Project, 2008).

3. Climate Control in Mediterranean Greenhouses. Common problems existing in the Mediterranean such as water salinity, excessive temperature and high vapour pressure deficit (VPD) are not properly taken into consideration by most commercial climate controllers. For instance, a fog system can use nearly 60% of the crop water uptake if ventilation and VPD are not controlled simultaneously (Montero, 2006). Lowering transpiration rate can mitigate the yield loss caused by salinity (Li and Stanghellini, 2001). Stanghellini and Kempkes (2008) presented results on a controller that maintained a desired transpiration rate by managing ventilation and fogging. By doing so, interesting year-round reduction on energy costs for humidity control plus valuable decrease in the need for ventilation was achieved. This makes it possible to increase the CO_2 concentration. Other attempts to control humidity by using ventilation and fog systems are based on the stomate response to the environment (Voogt and van Weel, 2008).

More complex hierarchically structured year-round management of the greenhouse agro-system is being investigated by Rodriguez et al. (2008) among others. In this approach, the climate control is considered as a multi objective task with, sometimes, conflicting objectives. Three main objectives, such as maximising profit, fruit quality and water use efficiency were taken into consideration. There is no one solution that can optimise the three objectives, so each objective is weighted according to its given relevance. Short-term set points and long-term set-point adaptations are decided to find a compromise solution that satisfies and balances the three objectives.

Either short term time scale control or long term control, the systems require tuned modelling of the greenhouse climate and crop growth and development models as well. This sort of new look at the climate control problem by considering the crop response is a hot subject needed of further development of sensors, modelling and suitable algorithms, not only in the Mediterranean but in many other areas of the world.

CONCLUDING REMARKS

For all areas under consideration, attempts to design more efficient greenhouse systems are under way. In Northern Asia progress is being made towards the optimisation of the greenhouse as a solar collector and to the development of new heating strategies. Important subjects addressed in The Netherlands are energy conservation and the replacement or alleviation of human labour by increasing mechanisation. In the Mediterranean there is growing interest in semi-closed greenhouses with CO_2 enrichment and control of excessive humidity. All geographic areas share the need of having an optimized climate control based on the crop response to the greenhouse environment. Engineering and plant physiology must work closely together to reach this goal.

Needless to say that the environmental concern leads any future development, also in the greenhouse engineering. The impact of the greenhouse on its natural and social environment is not to be ignored, and growers are faced with challenges to reduce emissions to the air by fuel combustion, nutrient emission to the surface and ground water, pesticide emissions, etc. as well as reduction of light emissions. The greenhouse of the future will have zero emissions (EUPHOROS, 2009) independently of the location of such a greenhouse. Quantitative tools like the Life Cycle Assessment (LCA) are being used to evaluate the environmental impact of protected cultivation. Quantitative analysis, in confrontation with light opinions on environmental issues, are proving that greenhouse production, if properly managed, is not an unfriendly human activity. This is not meant to say that greenhouses do not have a negative burden on the environment. On the contrary, all actors involved in the greenhouse sector should have a firm compromise to identify the main factors affecting the environmental impact associated to their activity and to adapt appropriate technology to mitigate the problems.

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