Design of a Sustainable Innovation Greenhouse system for Turkey

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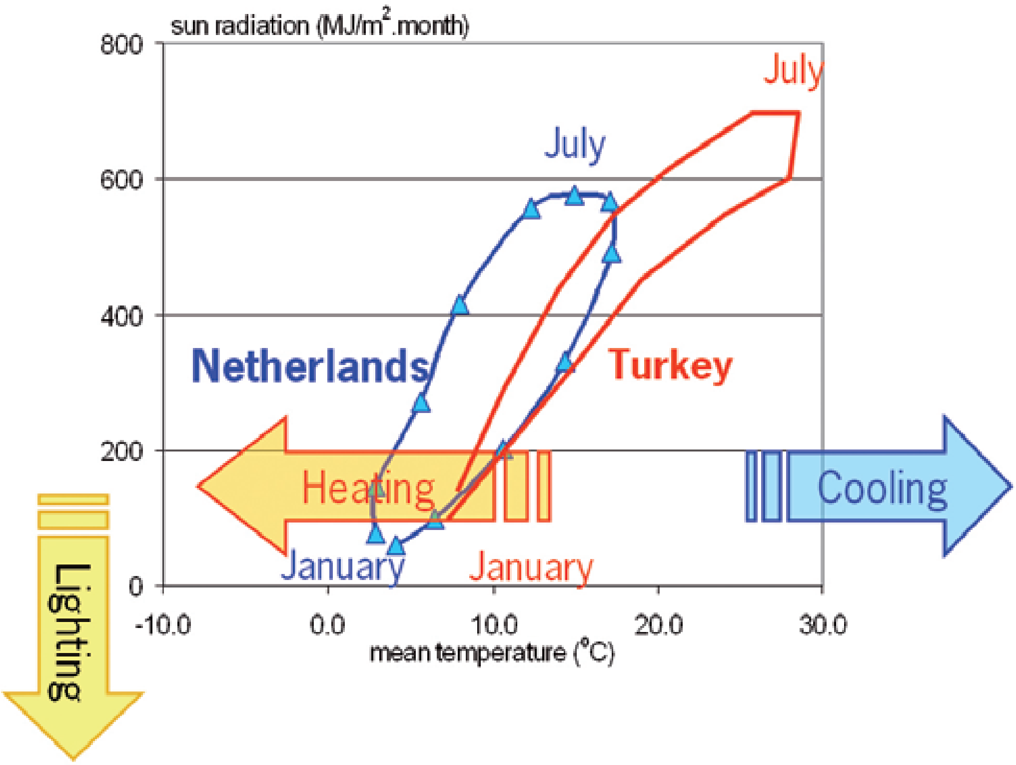

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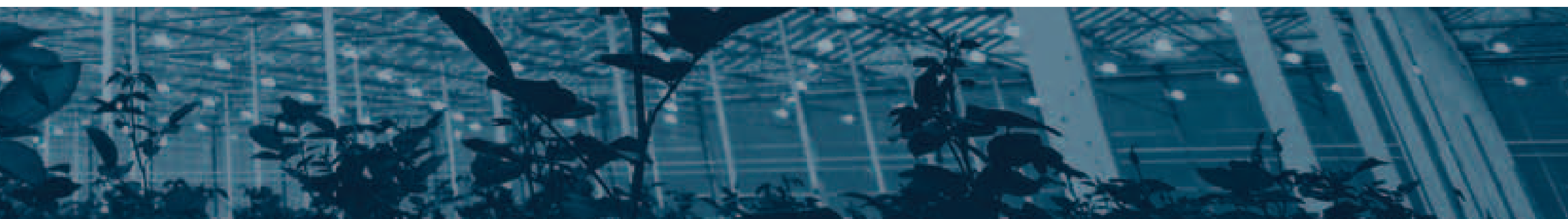

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1 Background

In scope of the program 2g@there in May 2008 an agreement was signed between EZ (EVD), LNV, AVAG, VRIAN and WUR. Turkish private investors and the local and central government were approached in 2008.
The goal of the program 2g@there is to increase the favourable position of Dutch technology suppliers and horticultural related business in Turkey and create sustainable and fruitful relationship between both. An activity in the program is establishing an innovative greenhouse and knowledge centre in one of the regions of Izmir/Aydin/Dikili, Burza, Antalya or Ankara. The innovative greenhouse will be designed specially to realize an environmental friendly and sustainable production system with low need of energy, water and nutrition. The name of the project is SeraCulture.

2 Introduction

Today, protected cultivation systems are used throughout the whole world for crop production. Areas with protected cultivation are still growing. Driving forces range from improved food production with higher production levels, extended growing seasons, decreased water use compared to open field production and/or diminished risks of crop failure by for instance storm, rain or hail and pests and diseases, to better quality and safer food products and a growing demand for convenience products like specialties, flowers and potted plants in Western-Europe.
A quick scan of the systems used throughout the world reveals that, a wide range of protected cultivation systems has evolved. Just like nature, the local conditions determine which designs are fitting and which are not. They range from low-tech, low-cost plastic tunnels to high-tech expensive glasshouses used in Western-Europe and North-America. Greenhouses differ in size, shape and materials used, ranging from single span structures covered with plastic to multi-span greenhouses with glass covers. Instrumentation ranges from unheated greenhouses with natural ventilation to production systems with computer controlled heating, cooling, humidification and dehumidification, CO_2-supply and artificial light. High-tech fully closed greenhouses are already installed in the Netherlands and Northern America. Crops are grown in soil, but also in artificial substrates with water and nutrient supply using drip irrigation and closed water circuits with drain water treatment. Manual labour is commonly used throughout the world, but in high-tech greenhouses the first robots have recently been introduced to replace human labour. There is a need to adapt a greenhouse design to the local climatic and socio-economic conditions and the availability of resources and legislation. For that a systematic design methodology is needed.

With these observations in mind, this study addresses the design of a protected cultivation system that satisfies the local conditions in the region considered, here the Western part of Turkey. Definitely, this question is not raised for the first time. An abundance of literature exists in which various design issues have been tackled, related to greenhouse structure and greenhouse covering materials (*e.g.* Von Elsner *et al.,* 2000a,b), to optimize the greenhouse design to one specific location or to one single construction parameter (*e.g.* Hemming *et al.*, 2004; Impron *et al.*, 2007; Zaragoza *et al.*, 2007), to optimize climate conditioning (*e.g.* Garcia *et al.*, 1998), greenhouse climate control (*e.g.* Bakker *et al.*, 1995) or substrates and nutrition control (*e.g.* Gieling, 2001), to mention just a few examples. But in most of these studies greenhouse design is approached as a single factorial problem, which means that only one issue is being considered which may lead to a sub-optimal design. However, it will be clear that the design of protected cultivation systems in fact is a multi-factorial design and optimization problem (van Henten *et al.*, 2006, Hemming *et al.*, 2008), several factors have to be addressed to find the optimum design.

The question raised here is: What is the optimum greenhouse design for the Western part of Turkey? Which design is needed to develop an innovation greenhouse in the most sustainable way but also in the most economic beneficial way? In this study a sustainable innovative greenhouse will be designed for the Western part of Turkey. The goal is to realise an environmental friendly production system with low energy input, use of sustainable energy, high water use efficiency, high production and predictability of production, high product quality resulting in potential high market prices, high food safety and high ratio of benefit and costs of the production system.

One of the most important factors influencing the optimum greenhouse design is the given outside climate of a location. It strongly influences the greenhouse inside climate and therefore crop production inside the greenhouse to a large extend. Hanan (1998) and Van Heurn and Van der Post (2004) have identified some other factors that determine the particular choice of the protected cultivation system used. A combination and extension of their lists of factors:

1. Market size and regional physical and social infrastructure which determines the opportunity to sell products as well as the costs associated with transportation.
2. Local climate, which determines crop production and thus the need for climate conditioning and associated costs for equipment and energy. It also determines the greenhouse construction dependent of, for example, wind forces, snow and hail.
3. Availability, type and costs of fuels and electric power to be used for operating and climate conditioning of the greenhouse.
4. Availability and quality of water.
5. Soil quality in terms of drainage, the level of the water table, risk of flooding and topography.
6. Availability and cost of land, present and future urbanisation of the area, the presence of (polluting) industries and zoning restrictions.
7. Availability of capital.
8. The availability and cost of labour as well as the level of education.
9. The availability of materials, equipment and service level that determines the structures and instrumentation of the protected cultivation systems.
10. Legislation in terms of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air.

The factors listed above are not all taken into account into this study. The main focus will lay on the local climatic conditions, special attention will be given to the availability of electric power, energy sources, water, local costs and prices, as well as to prices of equipment. The availability of capital will be estimated to be no problem, since this project is focussed on large investors in the Western part of Turkey. The solution therefore can be different from solutions for small scale Turkish farms in other regions of Turkey. Equipment and cultivation systems will be imported to Turkey, since this is one of the goals of the 2g@there project SeraCulture, for which this study is done for. On the other hand the economic cost and benefit ratio will play a major role in the decisions made next to several indicators of sustainability.

3 Materials and Methods

3.1 Design methodology

Designing protected cultivation systems is a multi-factorial optimization problem as described above. During the design process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, light management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, market, legislation and availability of resources, the degree of technology chosen. The choices made also strongly influence the economic result.

To push the multi-factorial design of protected cultivations systems, a general design method is suggested here. It is based on systematic design procedures that have been described by for instance Van den Kroonenberg and Siers (1999) and Cross (2001). The design procedure roughly contains the following steps:

0. Definition of the design objective, (here: design of a sustainable innovation greenhouse for Western Turkey).
1. In a brief of requirements the specifications and design objectives are stipulated (here: low energy input, use of sustainable energy / geothermal heat, high water use efficiency, high production and product quality and predictability of production, high food safety by low pesticide use, high ratio of benefit and costs of the production system).
2. A systems analysis will reveal the functions needed, (here: heating, cooling, humidification and dehumidification, CO_2 application, water and nutrient supply, light management).
3. Derivation of alternative working principles for each function which yields a so-called morphological diagram. For example, in case of cooling we may consider natural ventilation, recirculation fans, fogging systems, pad-and-fan cooling or even air-conditioning systems with heat exchanger as design alternatives. Similar alternative working principles have to be described during this phase for the other functions.
4. Concept development stage. During this stage, the different functions, or more specifically working principles in the morphological diagram, are combined into a conceptual design that should at least satisfy the functional requirements stated in the design specifications. Several different concepts are designed at this stage, (here: different degrees of technology are applied: greenhouse with only heating and cooling by natural ventilation, greenhouse with heating and cooling by fogging, greenhouse with heating, fogging and CO_2 application etc.).
5. Design evaluation and bottle-neck assessment. During this stage the various conceptual designs are evaluated in view of the design requirements stated above. Design evaluation is based on expert assessment and on quantitative simulation using mathematical models (here: dynamic greenhouse climate models, CFD models and economic models).
6. For the conceptual design(s) chosen, each working principle has to be worked out in more detail, (here: greenhouse climate setpoints and cropping strategies are defined in more detail).
7. The design prototype is built and tested in view of the design requirements.

The advantages of such a design procedure can be summarized as follows. It prevents jumping too quickly to a solution while not having looked into the overall design problem seriously. It offers the opportunity for a multi-disciplinary approach to systems design. It prevents trial and error. It produces a good overview of the design requirements and reduces the chance of overlooking some essential design requirements. Bottle-necks and design contradictions are identified at an early stage. It offers insight into design alternatives and economical perspectives. It offers a basis for sound and objective decisions during the design procedure. By producing insight, stake-holders and decision makers can contribute to the process and are more easily convinced of the correctness of the design. Clearly, such a design method guides the engineer in the design process, but it does not guarantee success. In depth assessment of promising concepts with adequate models (here greenhouse climate, crop and economic models) and decision support systems helps to increase the success rate.

3.2 Description dynamic climate model Kaspro and input data

Crops are cultivated in greenhouses to protect the canopy for unfavourable weather conditions and possibly to enhance the quality of the growing environment. In principle, a closed envelope enables to control all relevant variables. However, since controlling variables is costly, in terms of investments and running costs, a well designed greenhouse is based on smart decisions on the bandwidth in which growing conditions can be influenced.

The most precious variable that affects growth is the light input to the greenhouse. By using a transparent structure, for weather conditions in the Western part of Turkey, some 10.000 moles of photosynthetic active radiation from the sun can be fed to the crop. Providing that the greenhouse design prevents from harmful climate conditions, this input of free solar radiation has a potential biomass production of at least 10 kg of dry matter per m^2 per year. When growing tomatoes, such a dry matter production could result in something like 100 kg of good quality fresh weight a year. In case a same amount of 10000 moles of photosynthetic radiation would be produced by artificial illumination, the best devices currently available would use 1750 kWh of electricity per m^2 per year. This simple computation shows why greenhouses are made from transparent materials. The input of light, however, means an input of thermal energy as well, every envelope that grows a canopy has to be cooled and dehumidified. Cooling is needed because plants have an optimal growing temperature and above certain threshold temperatures plants will even die. Dehumidification is needed because plants have to evaporate in order to transport nutrients from the roots to the other plant organs. Moreover, high humidities enhance the growth and development of fungi that harm the crop. Cooling and dehumidification can be achieved by means of air-conditioning units or by air exchange with the outside. Obviously, when outside air conditions are favourable, the cooling capacity of the outside air is large, but when outside conditions are in about the same temperature and humidity conditions as the conditions that are wanted to be achieved inside the greenhouse, the cooling capacity is very limited. During those difficult periods, artificial cooling by means of air conditioning units could be interesting.

For the evaluation of various designs of greenhouse systems, several decision support systems have been developed such as KASPRO (de Zwart, 1996), SERRISTE in France (Tchamitchian *et al.*, 2006) or HORTEX (Rath, 1992) or GTa-Tools (Van 't Ooster, 2006). These systems support either designers or growers with reliable and quick assessment of energetic effects and crop responses of both the strategic and the operational choices.

In this study the KASPRO model is used. This extensive dynamic simulation model simulates a full-scale virtual greenhouse based on the greenhouse construction elements, ventilation openings, greenhouse equipment, different covering materials and their properties (transmission, reflection, and emission), set points for inside climate and the outside climate of a given location. Any computed physical quantity can be listed as output, but for the current project the observed output comprises the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water evaporated by the crop, the amount of CO_2 applied and the dry matter production of the crop.

The model is based on the computation of relevant heat and mass balances (Bot, 1983). The heat balances describe both the convective and radiative processes. The mass balances are constituted from exchange processes through leakage and ventilation (de Jong, 1990). They include canopy transpiration (Stanghellini, 1987) and condensation at cold surfaces. The mass balances around the CO_2-concentration are based on losses of CO_2 by ventilation and photosynthesis, and gains of CO_2 by dosing and respiration.

Basically, the model describes the entrance of solar radiation into a greenhouse structure and computes the heat and moisture fluxes induced from this radiation. The heat and moisture is released predominantly by the canopy, but the heat fluxes originate from other opaque elements in the envelope as well. Also, reflection of solar radiation, typically by the covering structure and by reflecting shading screens, is taken into account. The heat and moisture fluxes affect the air conditions around the canopy, which are in dynamic interaction with the greenhouse construction and the environment. To a certain extent, the interaction between the microclimate around the canopy and the environment can be controlled by means of heating, ventilation, humidification and dehumidification, CO_2 application, shading and optionally even by means of cooling.

Greenhouse climate is controlled by a replica of commercially available climate controllers. The total set of differential equations is solved numerically (de Zwart, 1996).
The control actions coming from the greenhouse climate controller are an integral part of the simulation model. According to user defined settings for the inside climate conditions that are to be achieved the controller increases or decreases the heating power, opens or closes the ventilation openings, applies fogging and CO_2 enrichment, opens or closes screening tissues and turns on artificial lamps. The temperature strategy comprises a daytime temperature setpoint for heating of 19 °C, a setpoint of 16 °C at the first part of the night period and a temperature setpoint of 18 °C in the second part of the night (starting at 02:00 'o clock). However, during the day, this 19 °C can be raised to 20.5 °C when the radiation intensity increases in the range from 100 to 300 W/m^2. Since avoiding high temperatures is a great concern, the ventilation setpoint is set only 2 °C above the heating setpoint. Thus, on a sunny day the greenhouse starts to ventilate at temperatures above 22.5 °C. When the greenhouse is 6 °C warmer than this starting point for ventilation (which means at 28.5 °C), all windows will be fully opened. In the hours around sunrise, some heat is put into the greenhouse to provide dry fruits and a dry canopy. This is achieved by a so called minimum pipe temperature of 40 °C, which means that the supply temperature of the heating pipes is prohibited to drop beneath 40 °C, irrespective the air temperature. Apart from a control on temperature, the windows can be opened on humidity. When the greenhouse air exceeds 85% relative humidity the windows are opened. The greenhouse is equipped with an energy screen that is closed during the night as soon as the outside air temperature drops below 14 °C. In the morning the screen is opened when the solar radiation exceeds 20 W/m^2.

Tomatoes are the crops chosen within this project. Generally, in Turkey, the new plants are planted in the greenhouse around the first week of august and the crop is removed from the greenhouse by the end of July. Different planting data are analysed.

For the SeraCulture -project, the KASPRO simulation model was used to analyze the effect of local outside climate conditions (chapter 4.1) on inside greenhouse climate and crop response with an assumed greenhouse configuration. The effect of cooling by natural ventilation or evaporative cooling by fogging was analysed. The effect of CO_2-dosing was computed and light control by means of a shading screen or artificial lighting was studied.
Cooling by natural ventilation might not be enough in a climate with high temperatures and high irradiations. Providing low outside humidity conditions, evaporative cooling by fogging helps then to improve the greenhouse indoor climate conditions on these days. The fogging capacity that has to be installed is dependent on the typical local outside climate conditions. A discussion on the effect of cooling by fogging can be found in chapter 4.2.1.
CO_2-dosing can increase the biomass production, but when the ventilation rates are high, large dosing capacities are required and do not contribute to sustainability since CO_2 is then released into the outside air. The model is used to select a suitable dosing capacity which is discussed in chapter 4.2.2.
In regions with radiation intensities as high as in the Western part of Turkey, the contribution of the highest intensities to the production can be much less than the contribution of the moderate intensities. Therefore, it has to be investigated if the application of a shading screen could be favourable in order to avoid too high temperatures in the greenhouse, whereas the decrement of photosynthetic potential remains limited. Chapter 4.2.3. discusses the effect of light control by shading screens. Light control by artificial light is discussed in chapter 4.2.4.

The result of all KASPRO simulations were the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water transpired by the crop, the amount of CO_2 applied and the dry matter production of the crop for different scenario's. These results were then used to feed the economical model (chapter 4.4) and to calculate several indicators for sustainability (4.5). At the end the results are used to make decisions on the optimum greenhouse design for Western Turkey (4.6).

3.3 Description of CFD model and boundary conditions

3.3.1 Numerical simulation using CFD

Computational fluid dynamics is a sophisticated design and analysis tool that uses computers to simulate fluid flow, heat and mass transfer, phase change, chemical reaction, mechanical movement, and solid and fluid interaction. The technique enables a computational model of a physical system to be studied under many different design constraints (Norton, 2007). A variety of reasons can be cited for the increased importance of simulation techniques achieved in recent years:

- Need to forecast performance.
- Cost and/or impossibility of experiments.
- The desire for increased insight.
- Advances in computer speed and memory (1:10 every 5 years).
- Advances in solution algorithms.

The dynamics of fluid flow is governed by continuity (conservation of mass), the Navier-Stokes (conservation of momentum), and the energy equations (conservation of energy). These equations form a system of coupled non-linear partial differential equations (PDEs). Because of the non-linear terms in PDEs, analytical methods can yield very few solutions. If the non-linearities in the governing PDEs cannot be neglected, which is the situation for most engineering flows; numerical methods are needed to obtain the solutions. CFD is an art of replacing the differential equation governing the fluid flow, with the set of algebraic equations (the process is called discretisation), which in turn can be solved with the aid of a digital computer to get an approximate solution. The well known discretisation methods used in CFD are Finite Difference Method (FDM), Finite Volume Method (FVM), Finite Element Method (FEM), and Boundary Element Method (BEM). The commercially CFD code Fluent 5.3, which is used in the present study, uses the FVM method.

By performing a CFD analysis the main benefits are:

1. Insight of the design: If we have a device or system design which is difficult to prototype or test through experimentation, CFD analysis enables us to virtually crawl inside our design and see how it performs. There are many phenomena that we can witness through CFD, which wouldn't be visible through any other means. CFD gives us a deeper insight into our designs.
2. Foresight of the design: Because CFD is a tool for predicting what will happen under a given set of circumstances, it can quickly answer many "what if" questions. By providing a set of boundary conditions, in relatively short time, we can predict how our design will perform, and test many variations until we arrive at an optimal result. All of this can be done before physical prototyping and testing.
3. Efficiency: The foresight we gain from CFD helps us to design better and faster, save money, meet environmental regulations and ensure industry compliance. CFD analysis leads to shorter design cycles and products get to market faster. In addition, equipment improvements are built and installed with minimal downtime. CFD is a tool for compressing the design and development cycle allowing for rapid prototyping.
4. Numerical Lab or Virtual Wind Tunnel: CFD results are directly analogous to wind tunnel results obtained in a laboratory – they both represent sets of data for given flow configurations at different Mach numbers, Reynolds numbers, etc. However, unlike a wind tunnel, which is generally a heavy, unwieldy device, a computer with the suitable CFD software is a readily transportable tool or a 'transportable wind tunnel' in which could be carried out a countless number of experiments with negligible cost.
5. Ability to Simulate Real Conditions: Many flow and heat transfer processes can not be (easily) tested (hypersonic flows, high temperatures, reactors, etc). CFD provides the ability to theoretically simulate any physical condition.
6. Ability to Simulate Ideal Conditions: CFD allows a great control on physical process, and provides the ability to isolate specific phenomena like the differences between laminar and turbulent flow. The advantages of such approach is one of the key factors why CFD tool is now a days playing major role in the design process of real life engineering applications.

There are essentially three stages to every CFD simulation process: Pre-processing, Solving and Post processing.

- Pre-processing: This is the first step in building and analyzing a flow model. It includes building the model within a computer-aided design (CAD) package, creating and applying a suitable computational mesh, and entering the flow boundary conditions and fluid materials properties. There are large numbers of commercial CAD packages for creating complex 3D geometries. In this study the commercial geometrical processor Gambit 1.2 was used.
- Solution: The CFD solver does the flow calculations and produces the results by solving the discritised form of governing equation. This stage needs clear understanding of flow physics involved in the problem. Fluent code, used in the present study, has been validated against many industrial scale applications, so real-world conditions could be accurately simulated, including heat transfer, mass transfer, multispecies flows, multiphase flows, reacting flows, rotating equipment, turbulence and radiation.
- Post processing: The enormous amount of data generated by CFD solver can not be analyzed by just looking at the numerical values. The final step in CFD analysis involves the organization and interpretation of the predicted flow data and the production of CFD images and animations. Different post-processing tools like colour contour and vector plots are used to go into the problem. The interpretation of these results plays an important role in determining the performance of any system being studied.

Greenhouses are essentially plant growth conditioners, where the microclimate parameters are maintained at levels consistent with the biological demands of the crop. A CFD analysis of the greenhouse environment expresses the interaction between the outdoor climate and the internal crop canopy. Quantitative understanding of a microclimate can help both greenhouse constructors and growers to optimize the design of the greenhouse and the operation of climate control systems respectively. It is an important modelling tool in order to evaluate the different greenhouse designs made during the design process. Due to the complexity of the phenomena involved in indoor production systems, the amount of information required, to fully quantify the environmental variables, is dependant both on the physics involved and the level of precision associated with the analysis tools. With the power of computers rapidly increasing, the ability to elaborate spatial and temporal analyses of the greenhouse microclimate with a reduced amount of expensive and time consuming experimentation is now possible. CFD application studies used in the advancement of greenhouse technology have been comprehensively reviewed by Boulard *et al.* (2002), Reichrath and Davies (2002) and Norton *et al.* (2007).

In the SeraCulture project, CFD models are used to optimise the process of cooling by different natural ventilation systems, recirculation fans and the application of fogging Next to that, the effects of light control by shading and thermal screens on greenhouse air flow and microclimate was were studied. Also, the CFD model was used to analyse the effect of insect nets for pest control and therefore the reduction of the use of pesticides was analysed using CFD models.

3.3.2 Design of 3D simulation models

The natural ventilation of greenhouses plays a key role to the overall concepts of heat and mass transfer processes. As the ventilation performance of greenhouses is strongly related to the ventilation capacity, by means of opening area, the effect of a continuous roof ventilation system was studied first.

In order to investigate the influence of increment the opening area to the ventilation performance, two variations of a typical Venlo-type greenhouse with a span width 9.6 m and 8.0 m respectively were designed and simulated. Both greenhouses were designed with a continuous roof opening width of 1.0 m, a gutter height of 6.0 m and a ridge height of 7.0 m, (Figure 3.1). The covered area for both designs was 1 ha (9984 m^2). The opening area was 3060 m^2 (31% of the covered area) and 3675 m^2 (37% of the covered area) for the greenhouse with span width 9.6 m and 8.0 m respectively (the second one has 20% more). Additionally the effects of applying side ventilation systems were analysed.

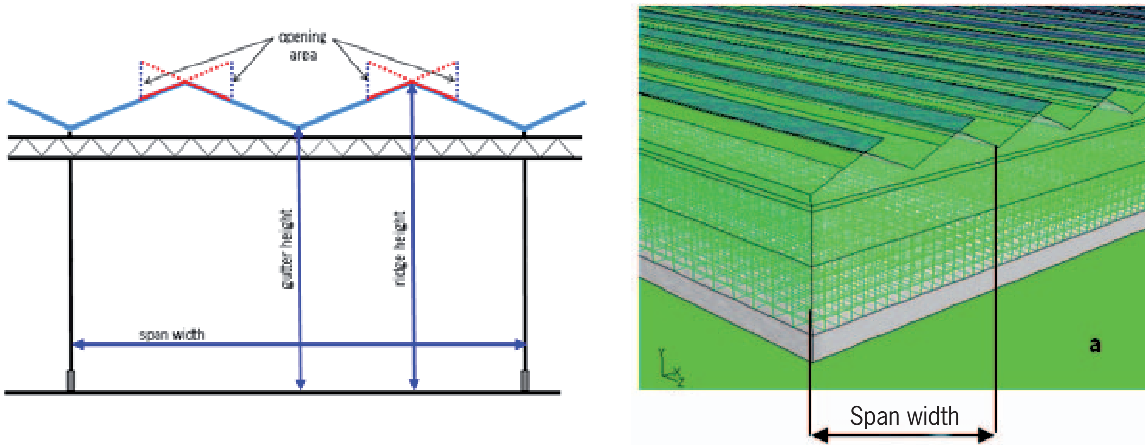


Figure 3.1 Design of a typical Venlo type greenhouse with continuous roof openings and different span width (9.60 m or 8.0 m)

The geometry processor Gambit 1.2 was used to design the computational domain around the greenhouse and to create the grid. The main target in this stage was to combine a grid with the smallest number of cells with acceptable accuracy concerning the simulation results. For all the cases a structured grid was used which ensures high quality. Both designs have almost the same number of computational cells (around 950000) and the same quality. This ensures that the results are grid independent and comparable. The final model is 3D full scale model extended from 0-230 m to x direction, from 0-180 m to z direction and from 0-30 m to y direction. The main dimensions of the 3D model for both the greenhouse and the surrounding are depicted in Figure 3.2.

After defining the geometry and the grid, different equipments such as cooling by recirculation fans or fogging system, light control by screens and pest control by insect nets were integrated in the final 3D model (Figure 3.3) and analysed. In addition, in order to investigate the influence of the size of the greenhouse to the computational results, a 3D simulation model with greenhouse area of 2 ha was designed (Figure 3.4).

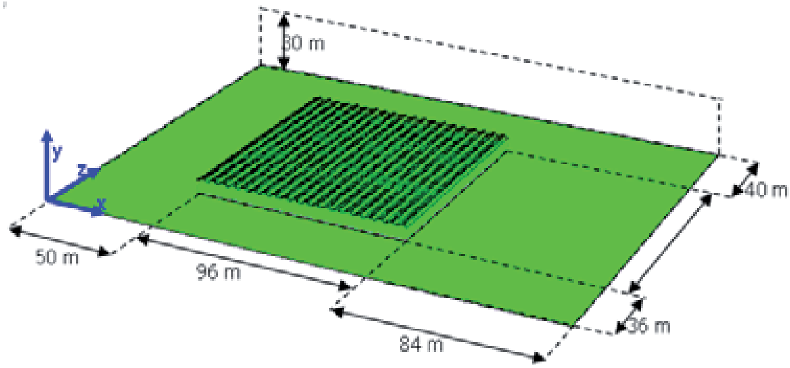
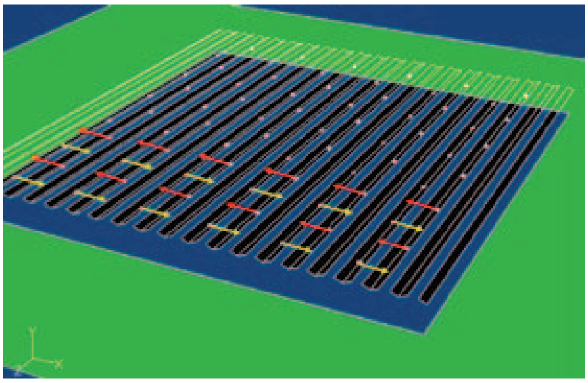


Figure 3.2 Dimensions of the computational domain consist of the 1 ha Venlo type greenhouse and its surrounding area



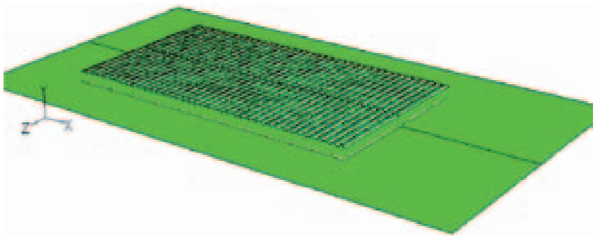


Figure 3.3 Simulation model of the greenhouse with span width 9.6 m and area 1 ha equipped with 72 recirculation fans (12 x 6) located 0.3 m below the gutter height

Figure 3.4 Simulation model of the greenhouse with span width 9.6 m and area 2 ha

As CFD models are totally deterministic models, next to grid quality and physical models (i.e. turbulence, wall functions, heat and mass transfer, etc), the results are depended on the boundary conditions. In this study the k-ε turbulence model with no-equilibrium wall functions (Fluent, 2008) was used in order to describe the ventilation process in the greenhouse (for more details see appendix). The boundary conditions define both inside and outside climatic conditions, crop behaviour and equipments and can be summarized as shown in table 3.1. For the inlet boundary condition a wind profile which is produced according the 'Log wind Profile' was used (for more details see appendix).

Table 3.1 Main constant input values used in 3D CFD model

Boundary element	Value	Unit
Outside conditions		
Outside air temperature	30 / 38	°C
Outside air relative humidity	50	%
Outside global solar radiation	800 / 1100	W m^{-2}
Wind speed (logarithmic profile)	1 / 3	m s^{-1}
Turbulence intensity	2	%
Turbulence length scale	0.04	m
External radiation temperature	-10	°C
Material properties		
Greenhouse cover transmission	0.75	–
Glass density	2500	kg m^{-3}
Glass specific heat capacity	840	J kg K^{-1}
Glass thermal conductivity	1	W m-1 K^{-1}
Wood density	700	kg m^{-3}
Wood specific heat capacity	2310	J kg K^{-1}
Wood thermal conductivity	0.173	W m^{-1} K^{-1}
Inside conditions		
Radiation reflected by canopy & construction	30	%
Crop (tomato)	porous media, power low model, C_o=1.7, C_1=1.65	
Ratio between sensible and latent heat	0.5	–
Sensible heat of plants	84 / 92.4	W m^{-3}
Latent heat of plants (mass flux of water vapour)	8.75 e^{-5} / 9.63 e^{-5}	Kg m^{-3} s^{-1}
Porosity of the plant canopy	1	–
Crop height	2.5	m
Initial mass flux of virtual gas (air-tracer)	$1x10^{-6}$	Kg m^{-3} s^{-1}
Equipments		
Insect nets (antithrips)	porous jump, permeability = $2.67e^{-10}$, thickness = 0.00018, pressure jump coefficient = 1.29	
Shading screen 30%	porous jump, permeability = $8.5e^{-05}$, thickness = 0.00065, pressure jump coefficient = 0.372	
Fogging system (heat sink)	300/-800 & 500/-200	gr m^{-2} h^{-1} / W m^{-3}
Initial mass flux of CO_2	0.012	kg m^{-2} h^{-1}

After defining the geometry and the grid and selecting the physical models and the right boundary conditions, the ventilation rate is calculated for the different scenarios. Natural ventilation is driven by two distinct mechanisms. The first driving mechanism is caused by thermal buoyancy, the so-called stack effect, which is dependent on the heating caused by incoming convective and radiative fluxes or by the metabolism of the occupant. The second mechanism, wind driven ventilation, is caused by the wind exerting pressure variations over the building envelope, and thus forcing airflow across ventilation openings.

One of the most important techniques for measuring ventilation and leakage rates is the tracer gas technique which is based on a mass balance of a tracer gas in the building air. There are three methods of measuring ventilation and leakage rates with tracer gas techniques; the decay tracer gas method, the method of constant injection and the method of constant concentration. In the most popular one, the decay tracer gas method, the building is initially enriched with a quantity of tracer gas and allowed to become well mixed to get uniform concentration. Sampling is then performed over time to document the rate at which the tracer gas concentrations decreases. The ventilation rate, in air changes per hour, can then be determined from this tracer decay rate. Tracer gas techniques area used not only for ventilation rate measurements but also for identification and characterization of air movement pathways, determination of volumetric flow and determination of re-entrainment.

In this study the ventilation rate of the greenhouses was calculated by simulating the method of constant injection of a tracer gas. In the simulation model the tracer gas is a virtual gas called “air-tracer” which has the same physical properties as air. The ventilation rate in $m^3 s^{-1}$ is given by Eq. 1.

$$\phi_{v,greenhouse} = \frac{\phi_{m,tracer}}{c_{tracer}} \quad (1)$$

Where $\phi_{m,tracer}$ is the constant mass flux of the tracer gas (air-tracer) in kg s^{-1} and c_{tracer} is the concentration of the tracer gas in the greenhouse in kg m^{-3}. The ventilation rate in $m^3 s^{-1} m^{-2}$ and in terms of air changes per hour is given by the Eq. 2 and Eq. 3 respectively.

$$VR_{greenhouse} = \frac{V_{greenhouse} \times \phi_{v,greenhouse}}{A_{greenhouse}} \quad (2)$$

$$VR_{greenhouse} = \phi_{v,greenhouse} \times 3600 \quad (3)$$

Where $V_{greenhouse}$ is volume of the greenhouse in m^3 and $A_{greenhouse}$ is the covered area of the greenhouse in m^2.

The major objective of the CFD-model work is to compute the maximal ventilation capacity of the greenhouse and the homogeneity of the temperature distribution. This maximal ventilation capacity is then used as a limitation quantity in the dynamic greenhouse simulation model (KASPRO). The KASPRO model can open and close vents (inducing a higher or lower ventilation rate) but should not exceed the maximum value as computed by the CFD-model (providing similar outside and inside conditions).

In the SeraCulture project, CFD models are used to optimise the process of cooling by different natural ventilation systems, recirculation fans and the application of fogging. Firstly the influence of the span width to the temperature distribution and ventilation performance was investigated in chapter 4.3.1. After, for the greenhouse design with the appropriate span width, several calculations were carried out in order to investigate the effects of different systems, like insect nets (chapter 4.3.2), shading, NIR reflecting screen and fogging system (chapter 4.3.3), recirculation fans (chapter 4.3.4) and CO_2 supply (chapter 4.3.5). Finally, the influence of the size of the greenhouse was investigated by performing similar calculations for a 2 ha greenhouse to ensure that the computational results are size independent.

3.4 Description of economic model and data collection

In an economic model several scenarios concerning different degrees of technology are analyzed in order to find the optimum greenhouse design for Western Turkey following the design method described in chapter 3.1. Glass and plastic film greenhouses are compared. Next to that an increasing degree of technology is analyzed.
The following table gives the different greenhouse design scenarios.

Table 3.2 Different greenhouse design scenarios considered in the economic study

	Venlo type (glass) Glass standard	Venlo type (glass) Glass CO_2	Venlo type (glass) Glass fogging	Venlo type (glass) Glass CO_2 & fogging	Venlo type (glass) Glass CO_2 & fogging & closed water system	Venlo type (glass) Glass CO_2 & fogging & closed water system & lighting	Turkish plastic Turkish plastic standard	Modern plastic Plastic standard	Modern plastic Plastic CO_2	Modern plastic Plastic fogging	Modern plastic Plastic CO_2 & fogging	Modern plastic Plastic CO_2 & fogging & closed water system
glass covering	x	x	x	x	x	x						
plastic film covering							x	x	x	x	x	x
heating	x	x	x	x	x	x	x	x	x	x	x	x
CO_2		x		x	x	x			x		x	x
fogging			x	x	x	x				x	x	x
soilless	x	x	x	x	x	x	x	x	x	x	x	x
open water system	x	x	x	x			x	x	x	x	x	
closed water system					x	x						x
simple climate control	x	x	x				x	x	x	x		
advanced climate control				x	x	x					x	x

The economic model is made based on the systematic calculation method given by KWIN (2008). Benefits are calculated versus costs on a yearly base. On one side the yield and product price of tomato are calculated as benefits, on the other side costs like heat, electricity and CO_2 consumption, plant material, labour costs, costs for crop protection, crop nutrition, water, substrate, plastic films, wires, clips and packaging with related cost prices are calculated as variable costs. Next to that the initial investments for installations like greenhouse construction, covering material, screening, insect netting, heating and cropping system, irrigation system, CO_2 dosing, fogging, artificial lighting, climate control and general costs for supervision, transport, packaging area, lifts, trolleys and machinery, roof washer, cold store are calculated per scenario. Initial investments are calculated back to annual costs by taking into account depreciation, maintenance and interest. The simple payback period is calculated by the total investment sum divided by the annual crop benefit – annual variable costs – annual maintenance costs.

Several input data for the economic quick scan are given by the model calculations described under chapter 3.2. The virtual greenhouse model KASPRO gives data for the tomato yield in terms of dry matter production, the heat, electricity, CO_2 and water consumption, which are used as input data for the economic model. The amount of plant material is assumed to be 2.5 plants per m^2. The costs for crop protection, crop nutrition, substrate, plastic film, wires and clips are taken from KWIN (2008) and are assumed to be comparable for Dutch and Turkish production. The labour costs are assumed to be 830 h per m^2 for 58 kg per m^2 and year of tomato following the KWIN (2008), for all scenarios the labour costs are assumed to vary in proportion to the yield. It is not considered that the labour costs are higher in the traditional Turkish situation due more manual work instead of the use of machinery. An open irrigation system is assumed to consume 40% more water than a closed irrigation system. The costs for packaging are assumed to vary with yield. In the case insect screens are applied, it is assumed that the costs for crop protection are 20% less due to the fact that less insects are penetrating the greenhouse. Prices for geothermal heat energy, electricity, CO_2 and labour are collected in Turkey via different Turkish and Dutch contact persons. All amounts of investments are given by different SeraCulture participants. Depreciation is assumed to be 4 years for plastic film covering material, insect netting, screening and CO_2 system. For all other installations it is assumed to be 15 years. Maintenance costs are 2%. Actual interest rates in Turkey are 6.5% (stand beginning of December 2009). The tomato price is estimated to be 0.90 €/kg, based on information from Turkey (export prices). Since no information was available for seasonal changes in product prices for greenhouse tomato in Turkey, we had to estimate the same price year-round. For all economic calculations a company size of minimum 2 ha is assumed. The total investment of the company is taken into account incl. general facilities and packaging area. An overview of assumptions of prices, costs and benefits are given in table 3.3, assumptions considering investments, depreciation, maintenance and interest rates and the resulting annual costs of investments are given in table 3.4.

Table 3.3 Assumptions of prices, costs and benefits for the economic model

	prices	source of information
price tomato [€/kg]	€ 0.90	Turkey
heat on geothermal base [€/m^3 gas equivalent]	€ 0.20	Turkey
electricity [€/kWh]	€ 0.13	Turkey
CO_2 [€/kg]	€ 0.175	Turkey
plant material [€/plant]	€ 0.50	KWIN
labor costs crop [€/h]	€ 2.50	Turkey
crop protection [€/m^2]	€ 1.00	KWIN
crop nutrition closed cycle [€/m^2]	€ 0.90	KWIN
crop nutrition open system [€/m^2]	€ 1.27	+ 40% compared to closed cycle
water [€/m^3] (water system, transpiration, fogging)	€ -	Turkey
substrate	€ 1.30	KWIN
plastic film, wires, clips	€ 0.50	KWIN
packaging	€ 0.01	KWIN

Table 3.4 Assumptions of investments, depreciation, maintenance and interest for economic model

	investment [€/m²]	depreciation [%/year]	maintenance [%/year]	interest rate [%/year]	annual costs investments [€/m²/year]	source of information
glass covering	€ 4.00	7	2	6.5	0.62	Dutch industry
plastic film covering	€ 1.80	25	2	6.5	0.60	Turkey
modern glass greenhouse incl. covering	€ 35.00	7	2	6.5	5.43	Dutch industry
modern plastic film greenhouse	€ 30.00	7	2	6.5	4.65	Dutch industry
Turkish plastic film greenhouse	€ 18.00	7	2	6.5	2.79	Turkey
heating & cropping system (gutters)	€ 16.00	7	2	6.5	2.48	Dutch industry
heating system Turkish greenhouse	€ 11.20	7	2	6.5	1.74	Turkey
screening system	€ 5.20	25	2	6.5	1.74	Dutch industry
insect netting	€ 4.70	25	2	6.5	1.57	Dutch industry
CO_2 dosing	€ 2.10	25	2	6.5	0.70	Dutch industry
fogging system	€ 3.00	7	2	6.5	0.47	Dutch industry
irrigation system open	€ 3.00	7	2	6.5	0.47	Dutch industry
irrigation system with re-circulation and disinfection	€ 5.00	7	2	6.5	0.78	Dutch industry
artificial lighting	€ 40.00	7	2	6.5	6.20	Dutch industry
climate computer simple	€ 3.00	7	2	6.5	0.47	Dutch industry
climate computer advanced	€ 3.50	7	2	6.5	0.54	Dutch industry
Diverse: transport, packaging area, lifts, trolleys and machinery, roof washer, cold store	€ 19.48	7	2	6.5	3.02	Dutch industry
Diverse: transport, packaging area, machinery, cold store Turkish greenhouse	€ 14.61	7	2	6.5	2.26	75% of Dutch costs are estimated

All investments are per m² greenhouse ground area

A sensitivity analysis is carried out by varying prices for the produce, prices for energy and CO_2 as well as costs for labour, greenhouse construction and installations and the interest rate in Turkey. The effect of those variations on the annual balance of benefits and costs and the simple payback period are analysed. In table 3.5 an overview of the parameters used in the sensitivity analysis is given.

Table 3.5 Parameters used in the sensitivity analysis

	unit	variation
price tomato	€/kg	0.5-1.3
price energy	€/m^3 gas equivalent	0.1-0.5
price CO_2	€/kg	0.1-0.7
costs labor	€/h	2.5-20
total investment cost	€/m^2	30-190
interest rate	%	3-18

3.5 Indicators for sustainability

Literally sustainability means “to keep in existence” and implies long-term support and permanence of an activity. “Sustainable development meets the needs of the current generation without undermining the ability of future generations to meet their own needs” (Hall, 2001). This very basic criterion for development in the future seeks to balance production needs with ecological and social needs. In the horticultural sector, sustainability characterizes a production system that is able to maintain its productivity and usefulness to the society for an indefinite period of time. That system has to be resource conserving, socially supported, commercially competitive and environmentally friendly (Weil, 1990). Achieving sustainability generally implies a more efficient and effective use of technology (Acutt and Mason, 1998). Protected cultivation systems can be described in terms of efficiency of the production process, resource use, impact on the environment and the social-economic impact (Castilla, 2002).

The following indicators for the Sustainable innovation greenhouse can be described in order evaluate the performance of the greenhouse a. after model calculations and design process and b. after realization of the greenhouse, practical measurements and actual data collection.

Efficiency of production process:
- Yield per area.
- Profit per area and year.
- Payback period.

Use of resources:
- Water per unit produce.
- Energy per unit produce.

Produce less environmental loads:
- CO_2 application per unit produce.
- Nutrient emissions.
- Pesticides applied per unit produce.

The different greenhouse designs are judged related to these indicators of sustainability. In the future more quantitative information has to be collected in practical measurements.

4 Sustainable innovation greenhouse for Western Turkey

Designing protected cultivation systems is a multi-factorial optimization problem as described in the introduction. During the design process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like local outside climate, market, legislation and availability of resources, the degree of technology chosen. The choices made strongly influence the economic result.
This chapter discusses a number of aspects associated with designing a suitable greenhouse for West Turkey's conditions, assuming that the resource of capital is enough to focus on a large scale sophisticated greenhouse. The optimum greenhouse design for the Western part of Turkey will mainly be based on the local climatic conditions, next to that the results are discussed in terms of the use of water, energy and other inputs, as well as local costs and prices of consumables and equipment. Special attention will be given to the availability of sustainable energy sources such as geothermal heat, and the availability of electric power from geothermal sources. The availability of capital will be estimated to be no problem, since we focus with this project on large investors in the Western part of Turkey. The solution therefore can be different form solutions for small scale Turkish farms. Equipment and cultivation systems will be imported to Turkey, since this is one of the goals of the 2g@there project SeraCulture, for which this study is done for. On the other hand the economic cost and benefit ratio will play a major role in the decisions made next to the indicators of sustainability. In this chapter the results of the study are shown based on the design methodology and models described in the chapter materials and methods.

4.1 Description of outside climate

The optimum greenhouse design for the Western part of Turkey will be strongly influenced by the local climatic conditions. In order to get a representative data file of the outside climate conditions of the Western part of Turkey, weather data from the airports of Aydin and Antalya were obtained (http://www.wunderground.com). Typically, these data comprise the temperature, humidity, wind speed and cloudiness of the weather. For Aydin, the data grid was only for values per day, but for Antalya these data were available on an hourly base.

The data about the cloudiness were used to construct the radiation data. Based on the latitude of the West of Turkey (37 °N), the course of the intensity of radiation on any clear day can be computed (radiation = 1200 * sin (elevation), W/m^2). Then, by combining the hourly maximum radiation with an observed cloudiness, a radiation profile resulted.

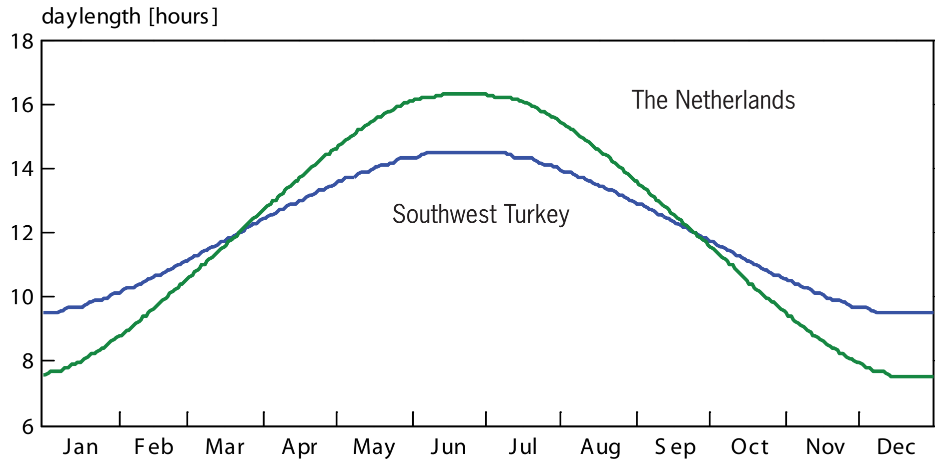


Figure 4.1 The course of day length in Turkey and in the Netherlands

One of the important differences between Turkish climate and the climate in the Netherlands is the fact that the day length varies a lot less in Turkey. This is shown in figure 4.1. The day length in summer in the Netherlands is significantly longer than in Turkey, but still the daily amount of radiation in Turkey is higher than in an average summer in The Netherlands. This is due to the fact that the sky in the Netherlands is generally cloudier. In summer, the Netherlands has some 200 hours of sunshine per month, whereas areas like Izmir or Antalya have 300 to even 350 hours of sunshine in the summer months.

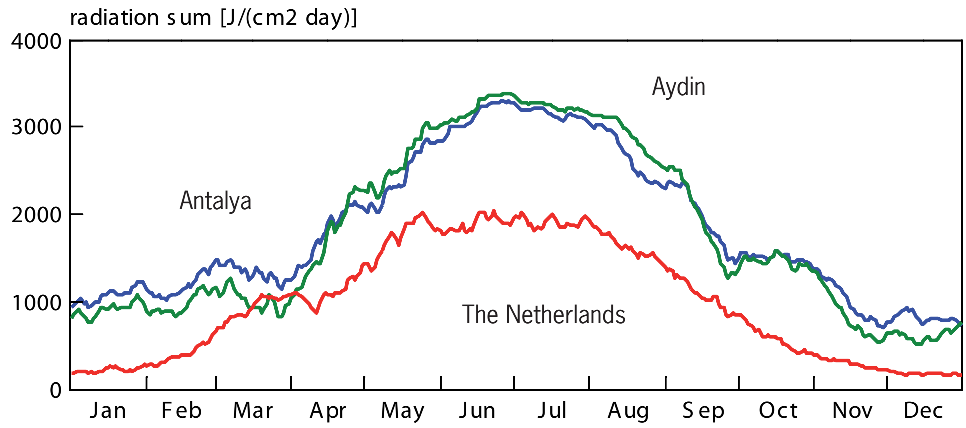


Figure 4.2 Daily radiation in two regions in Turkey in comparison to radiation conditions in The Netherlands.

Figure 4.2 shows the daily sum of radiation in a mean Dutch year and in 2008 and 2009 in Aydin and Antalya. Due to the higher radiation intensities, higher greenhouse temperatures have to expected, especially because the mean outside temperatures are higher as well. These outside temperatures are shown in figure 4.3, again together with the same meteorological quantity in an average year in The Netherlands.

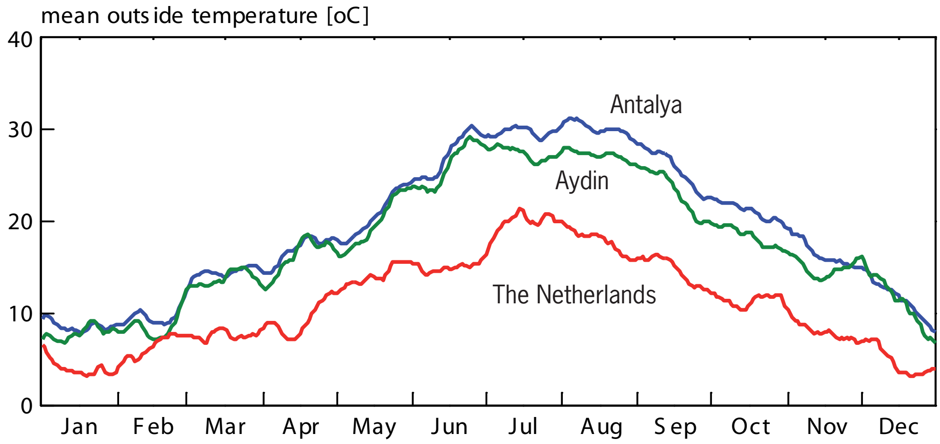


Figure 4.3 Daily mean temperature in two regions in Turkey in comparison to the temperatures in The Netherlands. The data were smoothed by a 14 days moving average filter.

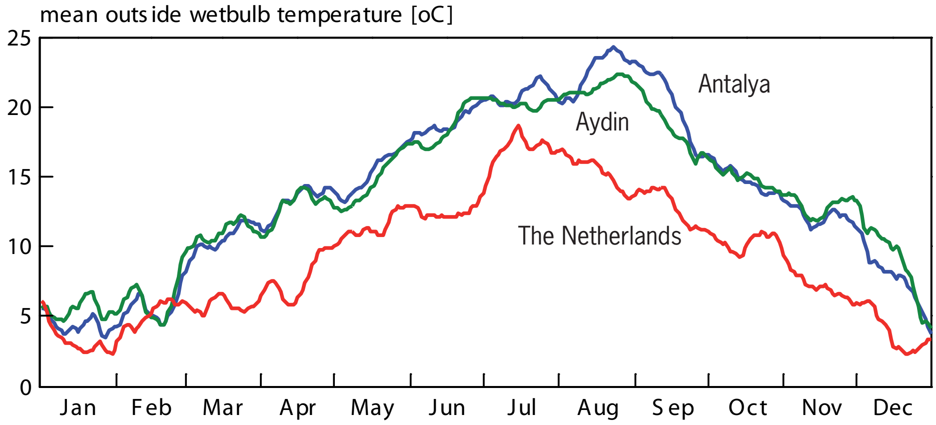


Figure 4.4 Daily mean wet bulb temperature in two regions in Turkey, together with the wet bulb temperature. The data were smoothed by a 14 days moving average filter.

However, for horticulture, it is not so much the outside (dry bulb) temperature, but mainly the outside wet bulb temperature that determines the cooling capacity of the outside air and therefore the resulting greenhouse inside temperatures. Figure 4.4 shows that the differences between Aydin and Antalya are small. Only in August, Aydin has a slightly lower wet bulb temperature, which makes Aydin a bit more favourable during the first month of growing the new crop during summer.

4.2 Results of dynamic greenhouse climate simulations

4.2.1 Fogging as a means of adiabatic cooling

The simplest method of cooling is by means of natural ventilation by large roof ventilation *e.g.* a continuous roof opening. Additionally cooling by means of fogging is useful to be considered. The application of fogging (also often referred to as misting) is getting more and more attention in horticulture worldwide. Especially in areas with high radiation intensities and low outside humidities (like regions Arizona and California in the United States and areas in the highlands of Andes-countries), fogging can contribute to more favourable greenhouse climate. In fact, fogging works along the same principle as the well known pad and fan systems, namely that dry air can be cooled by letting water evaporate. The major difference between pad and fans systems and fogging is the fact that fogging can easily be distributed through the greenhouse more evenly. Also, the electricity consumption of high pressure fogging installations is much less than the electricity consumption of ventilators that has to move lots of air through the greenhouse. A heavily used fogging installation will spray some 400 litres of water per m^2 per year, which consumes around 5 kWh per m^2 per year. The ventilators of a pad and fan system use at least a 10-fold of this amount.

The objective of fogging is in the first place to increase the humidity of the greenhouse during periods with high radiation in order to increase the enthalpy of the greenhouse air. The higher the enthalpy, the more energy can be carried off per m^3 air exchange between inner and outer greenhouse air. Since the ventilation capacity of a greenhouse is limited to something like 50 m^3 per m^2 floor surface per hour (especially when insect screens are mounted in the windows), improvement of the amount of energy that can be carried off to the outside means that greenhouse air temperatures become lower.

Table 4.1 Effect of fogging on the amount of unfavourable hot hours and the yearly amount of water sprayed by the system as a function of the capacity

Aydin

Fogging capacity	hours warmer than 30 °C	hours warmer than 35 °C	yearly sprayed water
No fogging	773	249	0
max 75 gr/(m^2 hr)	683	169	121
max 150 gr/(m^2 hr)	620	105	209
max 225 gr/(m^2 hr)	563	50	279
max 300 gr/(m^2 hr)	496	15	335
max 375 gr/(m^2 hr)	448	6	381

Antalya

Fogging capacity	hours warmer than 30 °C	hours warmer than 35 °C	yearly sprayed water
No fogging	824	274	0
max 75 gr/(m^2 hr)	688	190	137
max 150 gr/(m^2 hr)	610	110	233
max 225 gr/(m^2 hr)	538	58	302
max 300 gr/(m^2 hr)	479	19	349
max 375 gr/(m^2 hr)	434	6	383

In table 4.1 the effect of fogging is shown in terms of the number of hours with unfavourable high temperatures, defined as greenhouse temperatures above 30 °C and hours above 35 °C. In the reference situation, no fogging is applied. The table shows that especially the number of very hot hours is diminished significantly when a greenhouse is equipped with a fogging system that sprays something like 300-375 gram of moisture per m^2 per hour. Especially the crop canopy temperature can be reduced by the application of fogging, which is shown in figure 4.5.

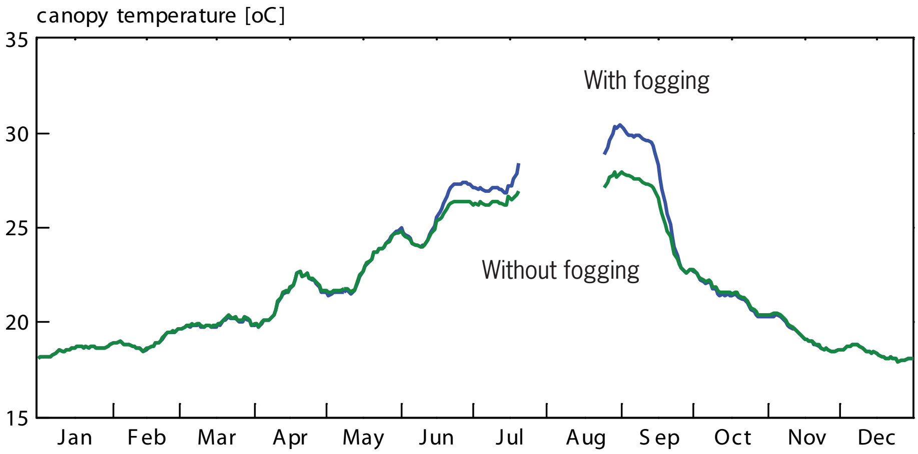


Figure 4.5 Daily mean canopy temperature in the greenhouse without the application of fogging (the blue line) and when using fogging with a capacity of 300 gram per m² per hour. The outside weather conditions in the region of Aydin are used.

Because of the application of fogging, the relative humidity of the greenhouse during daytime in summer will be significantly higher. This can be seen in figure 4.6. Especially at the start of the new canopy during summer, when radiation intensities are high, but the young crop is hardly capable to evaporate large amounts of water, the application of fogging improves the indoor climate a lot. By increasing the humidity to values above 60%, the evaporation from the plants is lowered, which results in less water stress.

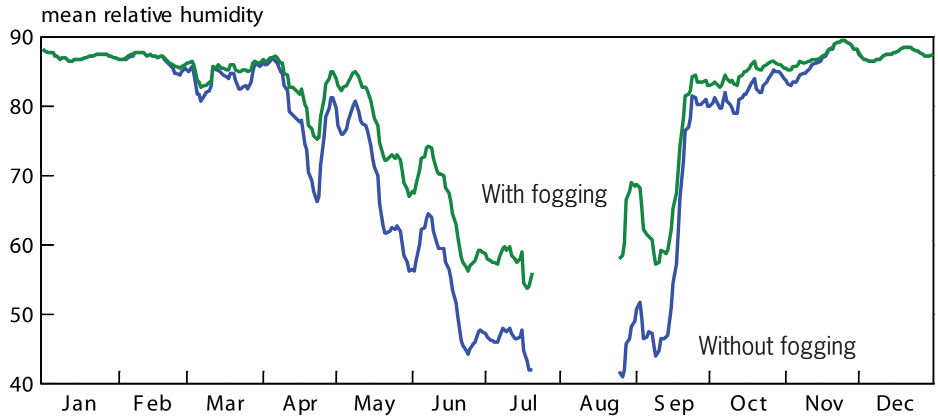


Figure 4.6 Daily mean humidity in the greenhouse without the application of fogging (the blue line) and when using fogging with a capacity of 300 gram per m² per hour. The outside weather conditions in the region of Aydin are used.

According to the data in table 4.1 and the graph in figure 4.6, a greenhouse built in the Western part of Turkey should be equipped with a fogging capacity of something like 350 gram per m² greenhouse surface per hour. Note that with this capacity, the actual mean fogging capacity is meant. In practice, the nozzles of a fogging installation are never running continuously, but apply the fog by pulses of water. This means that the capacity of the nozzles must be somewhere around half a litre per m² per hour. When this nozzle gives water for 45 seconds per minute, followed by a 15 seconds of rest, the actual fogging capacity will be 375 gram per m² per hour. The application of fogging is definitely recommended by the project group.

4.2.2 CO_2 dosing for production increase

Plant photosynthesis is mainly depending on the amount of light, temperature, humidity, CO_2, water and nutrients available at every moment. During summer time in the Western Turkey temperatures and light levels are high. Assuming water and nutrients can be applied to the extended needed, the amount of natural CO_2 will probably limit production. The CO_2-uptake of a full grown and healthy producing tomato plant reaches to levels around 45 kg per hectare per hour in case the carbon dioxide concentration in the greenhouse can be kept at 440 ppm. Since 440 ppm is a 60 ppm higher concentration than the outside, at a ventilation rate of 50 m^3/m^2 per hour, 55 kg per hectare per hour is lost to the outside. This means that, to maintain such equilibrium, 100 kg per hectare per hour must be added to the greenhouse to replenish the losses. Without such replenishment, the CO_2-concentration would drop to 340 ppm, but the CO_2-uptake by the canopy, and therefore the growth would drop to 40 kg per hectare per hour, meaning a more than 10% loss of production.
In periods with less bright light conditions, the ventilation rate is less and the effect of CO_2-dosing in terms of the increment of the ppm level in the greenhouse is much bigger than the 90 ppm elevation described above. When windows are opened only slightly, the concentration without additional supply drops a lot more, and the effect of adding external CO_2 is larger. Figure 4.7 shows the production effect of CO_2 dosing as a function of the dosing capacity. At the same time the amount of CO_2 added to the greenhouse increases with the dosing capacity. This is shown in figure 4.8.

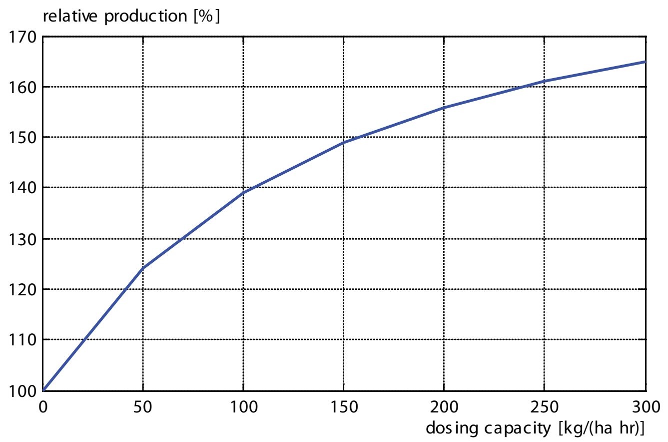


Figure 4.7 Increment of production (production without CO_2 is set to 100%) as a function of the CO_2 dosing capacity. The computations are performed for a greenhouse with a 300 gram per m^2 per hour fogging capacity. The outside weather conditions in the region of Aydin are used.

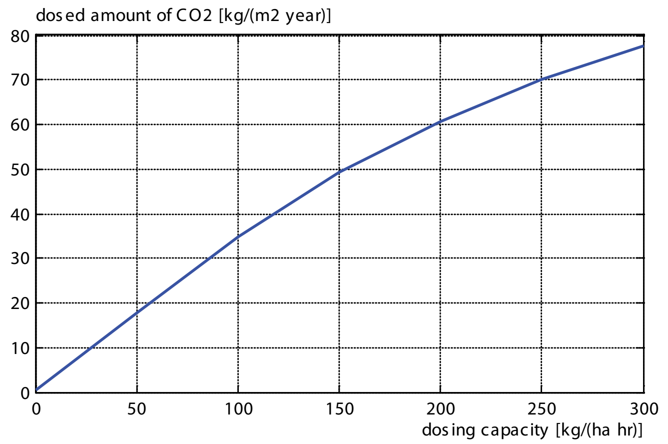


Figure 4.8 Yearly amount of CO_2 added to the greenhouse as a function of the CO_2 dosing capacity. CO_2 is supplied during daytime as long as the concentration doesn't exceed 900 ppm.

When looking at figure 4.7 and figure 4.8 together, it is obvious that de amount of CO_2 supplied, and thus the cost of CO_2, grows almost linearly with the capacity, whereas the effect becomes less. When coming from a situation without CO_2 dosing towards a capacity 50 kg/ (ha h), 18 kg CO_2 per m^2 per year is supplied, from which a 23% production increment is expected. When going to 100 kg/ (ha h), another 18 kg of CO_2 is supplied, but the production grows with 16%. The next step to 150 kg/(ha h) gives an extra consumption of 14 kg of CO_2 per m^2 per year and a production increment of only 10%. It is because of this declining added value of extra dosing capacity that made the decision to limit the recommended dosing capacity to 100 kg/(ha h), yielding a yearly total CO_2-supply of 36 kg/m^2 and an expected production that exceeds the production without CO_2-dosing with 38%. The application of CO_2 is therefore highly recommended by the project group, which will be confirmed by the economic calculations.

4.2.3 Screens for light control and energy saving

The control of natural light can be done by the application of shading screens. There are several possibilities of applying screens: shading and reduction of sun radiation energy input during summer, energy saving by reduction of heat energy output during winter or both in combination. For horticulture, the concern for a healthy growing crop is generally of more importance than achieving the highest possible energy saving during winter. The radiation intensities in the Western part of Turkey can be that high that some shading could be beneficial for the crop. The potential production during application in summer will drop when the source of growth, which is the solar radiation, is decreased. It is deliberated if the gain in crop quality and the decrement of risk could compensate for this loss of potential production. The table below shows the decrement in potential production for a shading screen that reflects 30, 40, or 50% of the radiation. In all cases the screen is closed when the outside radiation exceeds 700 W/m^2. The conclusion from table 4.2 is that the application of a 30 or 40% shading screen, which is closed when the outside radiation exceeds 700 W/m^2 gives only a small decrement in the potential production, whereas the heat load on the canopy is reduced significantly. This can be seen from the water consumption, which is reduced by around 10%.

Table 4.2 Effect of shading systems on the production, relative to the production without a screen and the effect on the total water consumption of the greenhouse (evaporation + fogging).

shading fraction	water consumption [m^3/(m^2 yr)]	production
No shading	1.217	100%
30% shading	1.090	94%
40% shading	1.067	93%
50% shading	1.034	90%

A shading screen is not air tight in order to ventilation not being limited too much. The fact that such a shading screen is not air tight means that the energy consumption increases by 10% if it is used during night-time in winter compared to an average energy screen. In absolute terms this means an increment with 2 m^3 of gas equivalents per m^2 per year. More energy could be saved by installing a highly aluminized winter screen. Such an energy winter screen cannot be used as shading summer screen, though. Therefore, traditionally in practical greenhouses, a combination screen with about 30% shading which is not air tight is used as a compromise.

The project group had a long discussion about the question which kind of screen is the best to be applied in the greenhouse. Screens can be very favourable, but the characteristics of an ideal screen vary with the season (winter/summer). In terms of an optimal effect of a screen on the greenhouse climate, multiple screening systems would be necessary. However, very high energy prices would be needed in order that the loss of energy saving due to the use of a sub-optimum screen would justify the installation of a second screening system. During winter, high insulating characteristics are required to save energy and to improve vertical temperature homogeneity in the canopy stand. This requires a highly reflective and air tight screen. During summer, the major concern of the grower will be to avoid high temperatures, which means that screens have to reflect solar radiation, but must not be air tight. This can be achieved by making the screen from reflecting strips in an open fabric structure. Especially the demands for the air tightness are the opposite in winter in comparison to summer. An overview about the different possible screens and screening strategies is given by the table below.

Table 4.3 Decision criteria for different screening systems

		No screen / only fogging			100% winter screen			NIR screen			Combined screen		
		pros	cons	no influence	pros	cons	no influence	pros	cons	no influence	pros	cons	no influence
Application	Winter (energy saving)		X		X			X			X		
	Summer (cooling)		X			X		X			X		
	Year round		X			X		X			X		
Operation - control	Easy to operate	X			X				X			X	
Inside climatic conditions	Air temperature (winter)		X		XXX			X			XX		
	Air temperature (summer)	X					X	X			X		
	Humidity (winter)			X	X			X			X		
	Humidity (summer)	X					X	X			X		
	Inside PAR	X				X		X	X			X	
	Inside NIR			X			X	X			X		
Crop - production	Production (winter)	X	X		X	X		X	X		X	X	
	Production (summer)	X					X	X			X	X	
	Total production	X			X			X			X		
Energy consumption	Energy saving (winter)		X		XXX			X			XX		
	Energy saving /water (summer)		X				X	X			X		
Cost	Installation	X				X			XXX			X	
	Operation - control	X				X			XX			XX	
	Maintenance	X				X			XX			XX	

From this table we can conclude that a screen is needed in order to have an additional steering parameter and to ensure crop yield and quality. Therefore, the project group suggests the application of a screen. Due to the very high costs, the NIR reflecting screen is not recommended by the project group. Thus, the project group suggests a traditional 30% shading screening system to be installed on half of the area of the Sustainable Innovation greenhouse. During operation of the greenhouse, the grower should try to use the screen in summer as less as possible in order to obtain maximal benefit from the solar radiation. Based on the results of the CFD calculations (chapter 4.3.3) we can conclude that fogging is more effective during summer to maintain lower greenhouse temperature than the application of a shading screen. Thus, the project group recommends to apply only fogging, no shading, during summer time in order to maintain the right temperatures inside the greenhouse and to install a highly aluminized winter screen on the other half of the area of the Sustainable Innovation greenhouse in order maximize energy saving and sustainability. Practical measurements have to show which alternative will be the best.

4.2.4 Potentials of artificial lighting

One of the possibilities to increase the production of a greenhouse is to increase the light input by artificial illumination. To investigate the effect of this extra light, the simulation model was used with the addition of high pressure sodium lamps (SON-T) with an electric power of 90 W/m² (this is about 10.000 lux or 140 μmol/ (m² s)).

The lamps were used from 1 October to 1 April and switched on at midnight. When the solar radiation exceeds 175 W/m² (outside the greenhouse) the lamps are switched off. In the evening, lamps are always switched off between 16:00 and 24:00. This strategy under Turkish light conditions result in 2400 hours of illumination and with the given electric power, the total electricity consumption is 214 kWh/m² per year.

The figure below shows that in the periods where the lamps are applied, the production grows substantially. On a yearly base, this artificial illumination is expected to give an additional 19 kg tomatoes per m² per year.

Apart form the high electricity consumption, the CO_2-consumption increases the production with 12 kg per m² per year. However, due to the heat brought into the greenhouse by the lamps, the heat demand drops to 10 m³ of natural gas equivalents per m² per year.

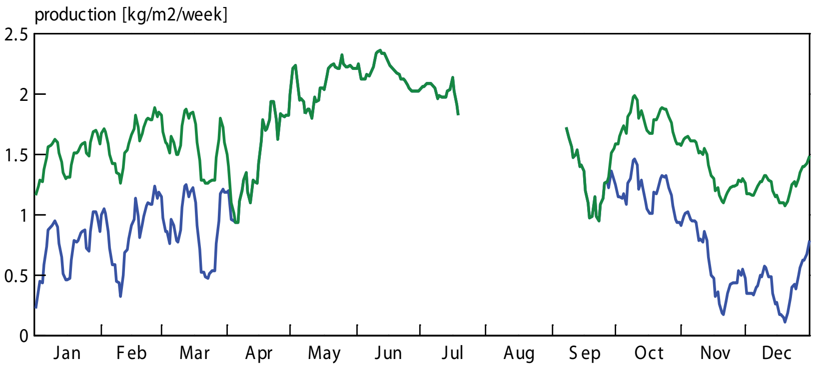


Figure 4.9 The result of the application of artificial lighting (blue line) during half of September until half of April on crop dry matter production.

Though the production increase is high, from the economic model it will be concluded that for Turkish conditions it will not be economic beneficial to apply artificial lighting for greenhouse tomato production.

4.3 Results of CFD simulations

4.3.1 Influence of span width on greenhouse microclimate

The simplest way of cooling is by means of natural ventilation. The influence of the span width to the ventilation performance was investigated by simulating two designs of a Venlo type greenhouse, with span width 9.6 m and 8.0 m respectively. Calculations, by simulating the decay tracer gas method, were performed for spring - summer conditions (i.e. outside air temperature = 30 °C, outside solar radiation = 800 W m^{-2}) since ventilation is an issue mainly during this part of the year. The computational results were evaluated in terms of ventilation rate, average air temperature inside the crop and the difference between minimum and maximum air temperature, which is an indication of the uniformity of the greenhouse environment. For all the cases only the leeward ventilation openings were considered to be completely open. The results are summarized in Table 4.4.

Table 4.4 Ventilation performance of two Venlo type greenhouses with span width 9.6 and 8.0 m respectively

	Boundary conditions		Greenhouse with span width 9.6 m			Greenhouse with span width 8.0 m		
	Wind speed, (ms^{-1}) / wind direction, (°)	Outside air temperature, (°C) / radiation, (Wm^{-2})	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)	Air temperature difference, (°C)	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)	Air temperature difference, (°C)
1	1 / 10°	30 / 800	66.64	38.46	5.97	75.63	37.80	4.65
2	1 / 45°	30 / 800	59.22	39.02	5.24	72.29	37.98	5.04
3	3 / 10°	30 / 800	69.64	37.64	5.90	78.95	37.22	5.43
4	3 / 45°	30 / 800	82.76	36.43	5.95	91.11	36.19	5.39

The greenhouse with a span width of 8.0 m performs better than the one with span width 9.6 m, as the average ventilation rate is higher with about 9.93 m^3 m^{-2} h^{-1} (15%). Decreasing the span width has a positive influence on air temperature distribution not only due to increased opening area but also due to more uniform distribution of this area on the greenhouse cover. In the greenhouse with span width 8.0 m the average air temperature in the crop area is 0.59 °C lower and the average temperature difference, between min and max values of the greenhouse area, is 0.64 °C lower, (Figures 4.10 - 4.13). At low wind speeds (1 m s^{-1}) the influence of decreasing the span width to ventilation rate is lower, when the wind direction is perpendicular; while at high wind speeds (3 m s^{-1}) is higher. Since the construction cost will be higher in the case of the greenhouse with span width 8.0 m (20% more for windows, insect nets and maintenance), the adoption of the design with span width 8.0 m is probably less attractive. Therefore, all the results presented in the next chapters concern the greenhouse design with span width 9.6 m.

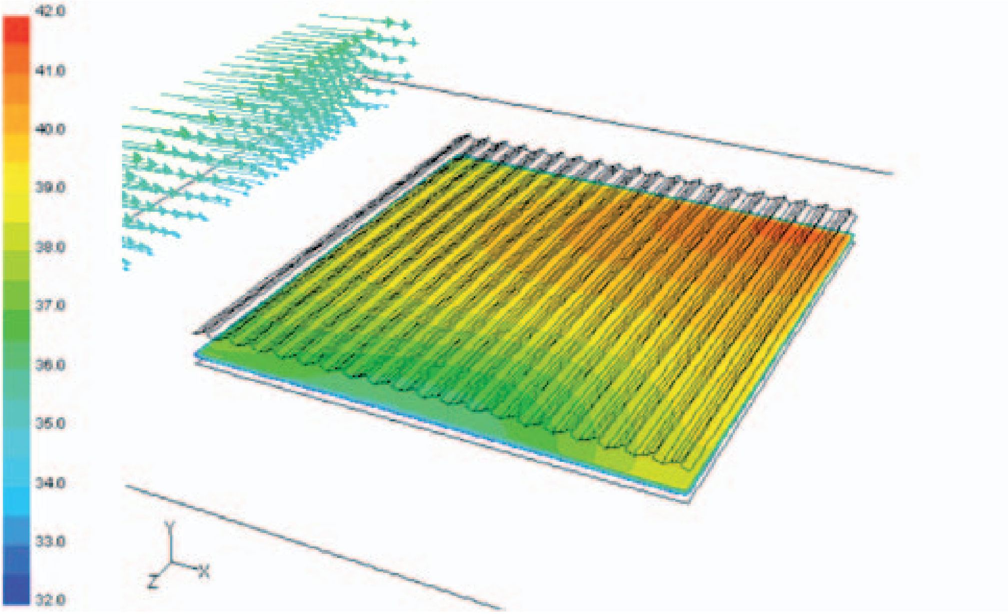


Figure 4.10 Air temperature distribution in a greenhouse with span width 9.6 m in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 3 m s^{-1} and wind direction 10°, min air temp: 35.07 °C, max air temp: 41.04 °C, difference air temp: 5.97 °C, ventilation rate: 66.6 m^3 m^{-2} h^{-1}, air changes per hour: 10.25).

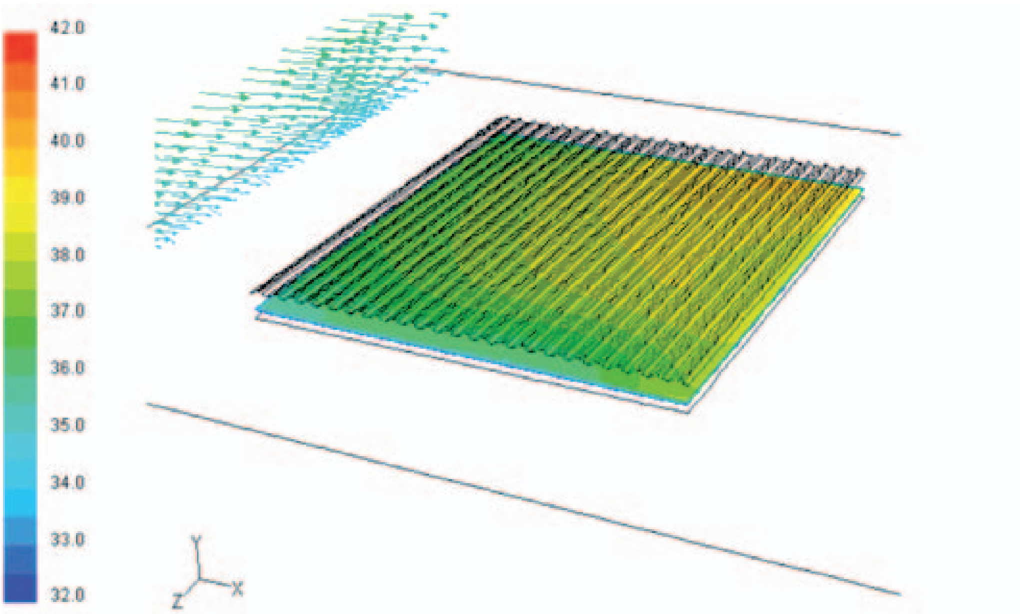


Figure 4.11 Air temperature distribution in a greenhouse with span width 8 m in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 35.00 °C, max air temp: 39.65 °C, difference air temp: 4.65 °C, ventilation rate: 75.6 m^3 m^{-2} h^{-1}, air changes per hour: 11.79).

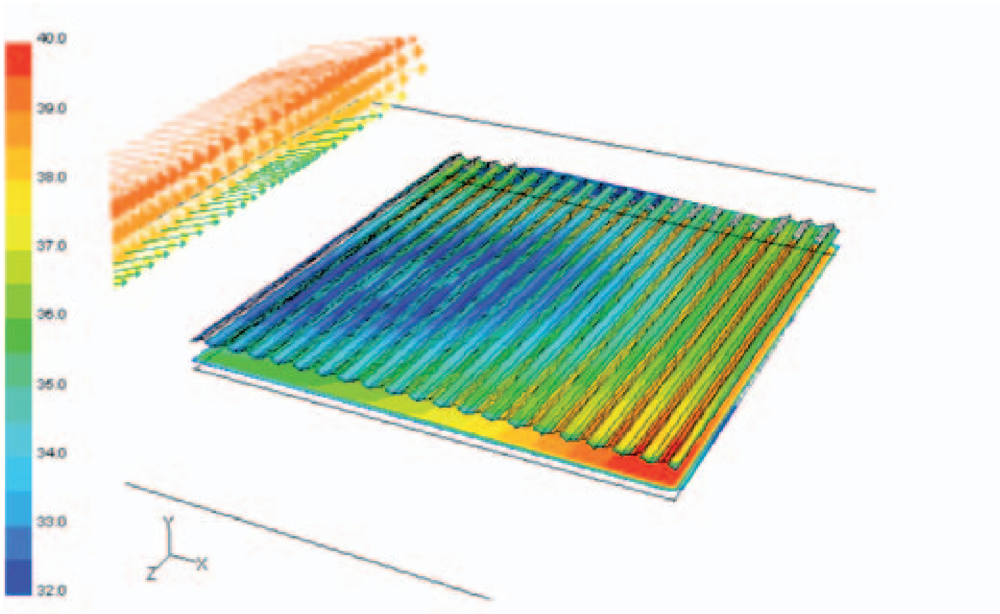


Figure 4.12 Air temperature distribution in a greenhouse with span width 9.6 m in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 3 m s^{-1} and wind direction 45°, min air temp: 33.90 °C, max air temp: 39.85 °C, difference air temp: 5.95 °C, ventilation rate: 82.8 m^3 m^{-2} h^{-1}, air changes per hour: 12.73).

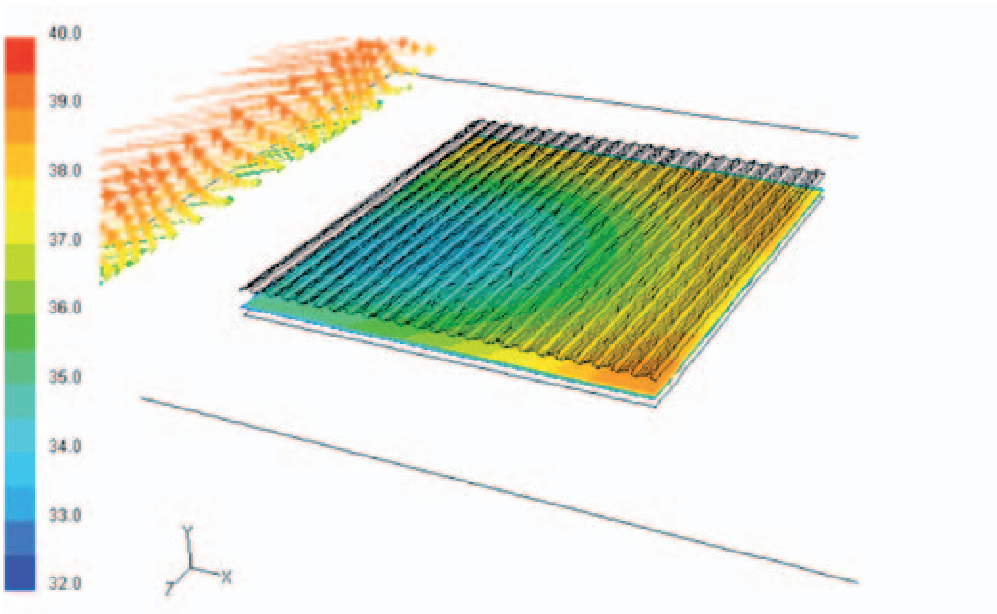


Figure 4.13 Air temperature distribution in a greenhouse with span width 8 m in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 3 m s^{-1} and wind direction 45°, min air temp: 33.60 °C, max air temp: 38.99 °C, difference air temp: 5.39 °C, ventilation rate: 91.1 m^3 m^{-2} h^{-1}, air changes per hour: 14.20).

4.3.2 Influence of insect nets on greenhouse microclimate

Covering ventilation openings and sidewalls of a greenhouse with insect-proof screens has the advantage of reducing the entry of insect pests into the greenhouse and therefore potentially reduces the amount of pesticides used. However, at the same time it affects greenhouse inside microclimate. The influence of insect nets to the ventilation performance was investigated by simulating a greenhouse with all ventilators covered with antithrips insect nets (the net with the higher resistance to the air flow due to low porosity). The simulations were performed for eight different scenarios regarding wind speed and direction, cooling by fogging, inside shading screen and side openings covered by insect nets. The computational results were evaluated in terms of ventilation rate, average air temperature inside the crop and the difference between min and max air temperature, which is an indication of the uniformity of the greenhouse environment. For all the cases only the leeward ventilators were considered completely opened. The results are summarized in Table 4.5.

Table 4.5 Ventilation performance and air temperature of 1 ha greenhouse equipped with antithrips insect nets

	Boundary conditions		Ventilation rate		Air temperature	
	Wind speed, ($m\ s^{-1}$) / wind direction, (°)	Outside air temperature, (°C) / radiation, (Wm^{-2}) / fogging / screen / side openings with nets	$m^3m^{-2}h^{-1}$	Air changes per hour	Average air temperature, inside the crop, (°C)	Min / Max / Difference
1	3 / 10°	30 / 800 / N / N / N	59.48	9.15	39.30	38.10 / 39.74 / 1.64
2	1 / 10°	30 / 800 / N / N / N	54.90	8.45	39.57	37.90 / 40.41 / 2.51
3	1 / 10°	30 / 800 / Y / N / N	44.59	6.86	32.73	31.20 / 32.98 / 1.78
5	1 / 10°	30 / 800 / N / Y / N	53.05	8.16	36.75	35.90 / 37.05 / 1.15
6	1 / 45°	30 / 800 / N / N / N	51.09	7.86	39.38	37.40 / 40.33 / 2.93
4	1 / 10°	30 / 800 / N / N / Y	83.92	12.91	37.28	33.50 / 39.13 / 5.63
7	1 / 45°	30 / 800 / N / N / Y	82.14	12.64	37.36	33.20 / 39.43 / 6.23
8	3 / 45°	30 / 800 / N / N / Y	86.29	13.28	36.95	31.00 / 39.60 / 8.60

Covering the ventilators with insect nets for a greenhouse with area of 1 ha results in a decrease of ventilation rate from 14%-18%. Even if there are few research studies in the literature dealing with the influence of insect nets to the ventilation rate, no one of them has been carried out for a Venlo type greenhouse yet. Most of these studies concern small experimental greenhouses and this is the reason why the influence of covering the ventilators with insect nets results in a much higher decrease of ventilation rate. For example, Kittas *et al.* (2002) calculated a reduction of ventilation rate at the order of 50%. However, in this study the measurements were done in a bi-span greenhouse with volume 690 m^3 and windows area of 52 m^2 (ratio 13.3), though a 1 ha Venlo type greenhouse has a volume of 64890 m^3 and windows area 2080 m^2 (for only one side of the span), (ratio 31.20).

Despite the obvious advantage of reducing insect pests by applying nets, the application of insect nets has positive influence to the air temperature distribution inside the greenhouse. Without insect nets the average air temperature difference between min and max values is 5.13 °C, while with insect nets is 1.77 °C, (Figures 4.14 & 4.15).

In order to overcome the reduction of ventilation rate due to insect nets, calculations were carried by simulating the same greenhouse but in this case considering roof and side openings both covered by insect nets, (Table 4.4, lines 4-7). The results show that a greenhouse with side and roof openings has a ventilation rate higher (at the order of 30%) even from a similar greenhouse with only roof openings without insect nets. However, the main disadvantage in this case is the poor uniformity of inside climate, since the average air temperature difference is around 6-8 °C.

Taking into account that side openings produce also difficulties regarding the application of CO_2, side openings seems to be not an option for an optimal design, (Figures 4.16 & 4.17).

In general however, the application of insect nets can be highly recommended, especially when additional fogging is applied in order to reduce inside temperatures (see below).

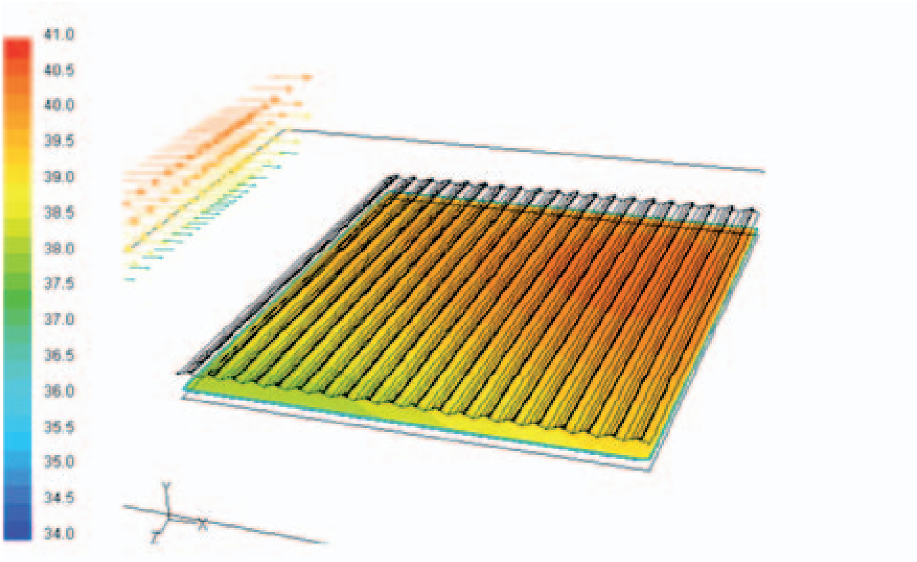


Figure 4.14 Air temperature distribution in a greenhouse with span width 9.6 m equipped with insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 3 m s^{-1} and wind direction 10°, min air temp: 37.90 °C, max air temp: 40.41 °C, difference air temp: 2.51 °C, ventilation rate: 55.1 $m^3 m^{-2} h^{-1}$, air changes per hour: 8.48)

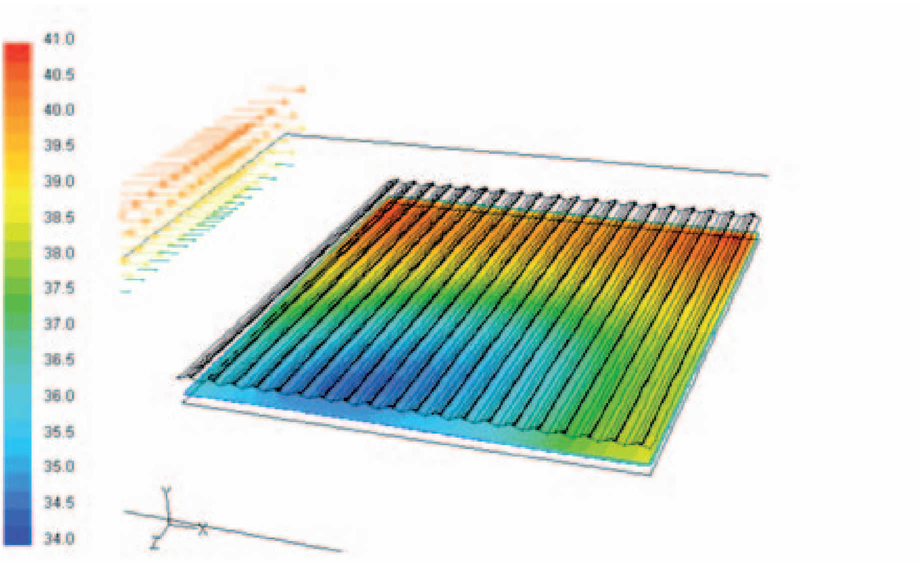


Figure 4.15 Air temperature distribution in a greenhouse with span width 9.6 m without insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 3 m s^{-1} and wind direction 10°, min air temp: 34.68 °C, max air temp: 40.58 °C, difference air temp: 5.90 °C, ventilation rate: 69.6 $m^3 m^{-2} h^{-1}$, air changes per hour: 10.71)

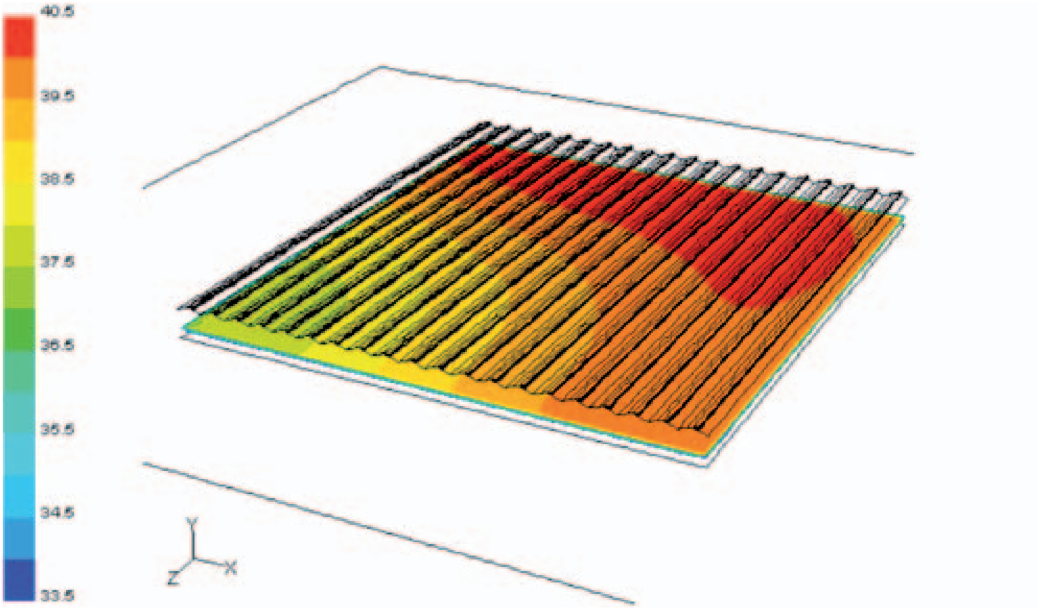


Figure 4.16 Air temperature distribution in a greenhouse with span width 9.6 m with insect nets and without side openings, in a horizontal cross plane surface at 2.0 m above the ground (wind speed 3 m s^{-1} and wind direction 45°, min air temp: 37.40 °C, max air temp: 40.33 °C, difference air temp: 2.93 °C, ventilation rate: 51.1 $m^3 m^{-2} h^{-1}$, air changes per hour: 7.86)

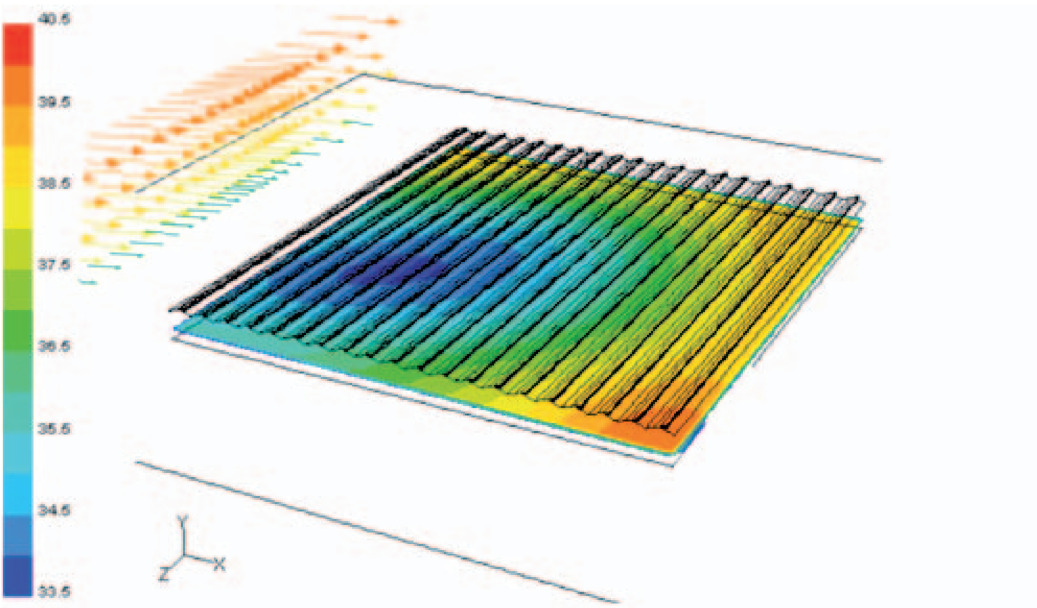


Figure 4.17 Air temperature distribution in a greenhouse with span width 9.6 m without insect nets, in a horizontal cross plane surface at 2.0 m above the ground (wind speed 3 m s^{-1} and wind direction 45°, min air temp: 34.68 °C, max air temp: 40.58 °C, difference air temp: 5.90 °C, ventilation rate: 69.6 $m^3 m^{-2} h^{-1}$, air changes per hour: 10.71)

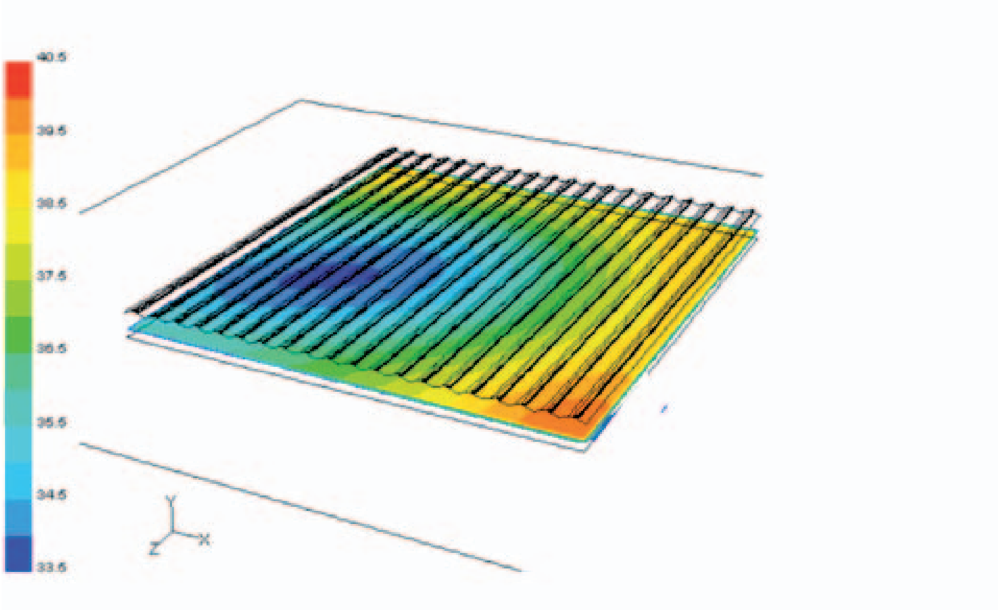


Figure 4.18 Air temperature distribution in a greenhouse with span width 9.6 m with insect nets to both roof and side openings, in a horizontal cross plane surface at 2.0 m above the ground (wind speed 3 m s^{-1} and wind direction 45°, min air temp: 31.00 °C, max air temp: 39.60 °C, difference air temp: 8.60 °C, ventilation rate: 86.3 m^{-3} m^{-2} h^{-1}, air changes per hour: 13.28)

4.3.3 Influence of applying fogging, shading screen or NIR reflecting screen

One of the most important issues in modern greenhouse cultivation is to extend the production season, in order to maximize the use of greenhouse equipment, extend export season, increase annual yield per unit area and increase profitability. Nevertheless, in many Mediterranean greenhouses such a practice is limited because the cooling method used, mainly ventilation and shading, does not provide the desired conditions, especially during the hot summer months.

The results regarding the ventilation performance of 1 ha Venlo type greenhouse, presented here above, indicate that there is a strong need for additional cooling next to natural ventilation. Direct evaporative cooling, applying an internal shading screen or a NIR reflecting screen are potential solutions. The principle underlying direct evaporative cooling is the easy conversion of sensible to latent heat while unsaturated air is cooled by exposure to free and colder water or water vapour, both thermal isolated from other influences. The principle underlying the shading screen is the reduction of solar radiation entering the greenhouse which implies a reduction air temperature while part of the radiation is converted to sensible heat. The NIR reflecting screen reacts as a normal shading screen but mainly for the infrared part of the sun radiation (700-2500nm), which means that the part of radiation that is useful for the plants (PAR, 400-700nm) is transmitted through the screen with minimum loss.
The performance of these different cooling principles was investigated by simulating a 1 ha Venlo type greenhouse with fogging system, shading system, NIR reflecting screen or a combination of these systems, (Figures 4.19 - 4.20). The computational results are summarized in Table 4.6.

The calculations show that a fogging system is able to keep the inside air temperature at affordable levels for the crop, even under extremely warm outside conditions (outside air temperature: 38°C, solar radiation: 1100 W m^{-2}, outside humidity 50% and maximal inside humidity 95%). The fogging system has a negative influence to the ventilation rate, since the stack effect, which has a key role to the ventilation phenomena, is less. By applying an internal shading screen (30%), the air temperature inside the greenhouse is higher than applying fogging with a capacity of 300 g m^{2} h^{-1}, even if the ventilation rate is lower. Finally, by combining the same fogging system with a NIR reflecting screen the air temperature inside the greenhouse is at the same level as it is when a fogging system with higher capacity is applied (500 g m^2 h^{-1}). Even if the cooling efficiency of the combination of NIR screen with a fogging system seems to be almost the same with the efficiency of a fogging system with high capacity (500 g m^2 h^{-1}), the advantages of this combination, neglecting the cost, are the higher evapotranspiration rates during spring-summer conditions and the use of NIR screen during winter. However, due to economic reasons the NIR reflecting screen can not be recommended. The project group supposes to use a 30% shading screen on half of the area of the Sustainable innovation greenhouse. On the other half of the greenhouse only a fogging system is supposed for summer climatisation combined with a high aluminized winter screen for energy saving purposes (see chapter 4.2.3).

Table 4.6 Ventilation performance of two Venlo type greenhouses with span width 9.6 and 8.0 m respectively

	Boundary conditions		Fogging system				NIR screen[1]		Internal shading system 30%	
			300 g m^{-2} h^{-1}		500 g m^{-2} h^{-1}					
	Wind speed, (ms^{-1}) / wind direction, (°)	Outside air temperature, (°C) / radiation, (Wm^{-2})	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)	Ventilation rate, ($m^3m^{-2}h^{-1}$)	Average air temperature, (°C)
1	1 / 10°	30 / 800	44.59	32.73						
2	1 / 10°	30 / 800							53.05	36.75
3	1 / 10°	38 / 1100			–	34.5				
4	1 / 10°	38/ 1100					–	35.0		

1: NIR screen is combined with a fogging system which consumes 300 g m^{-2} h^{-1}

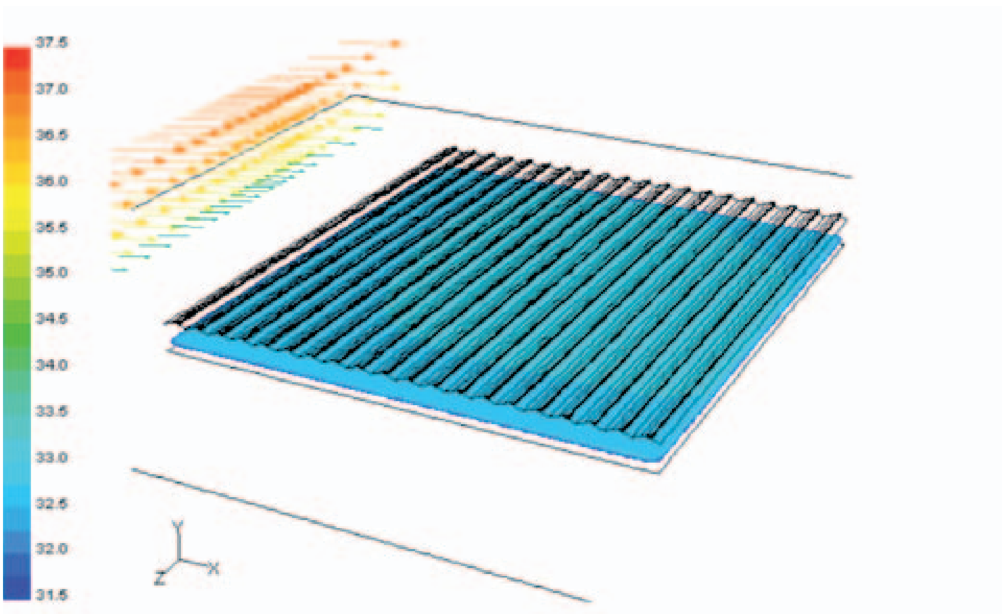


Figure 4.19 Air temperature distribution in a greenhouse with span width 9.6 m equipped with insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 31.20 °C, max air temp: 32.98 °C, difference air temp: 1.78 °C, ventilation rate: 44.6 m^3 m^{-2} h^{-1}, air changes per hour: 6.86)

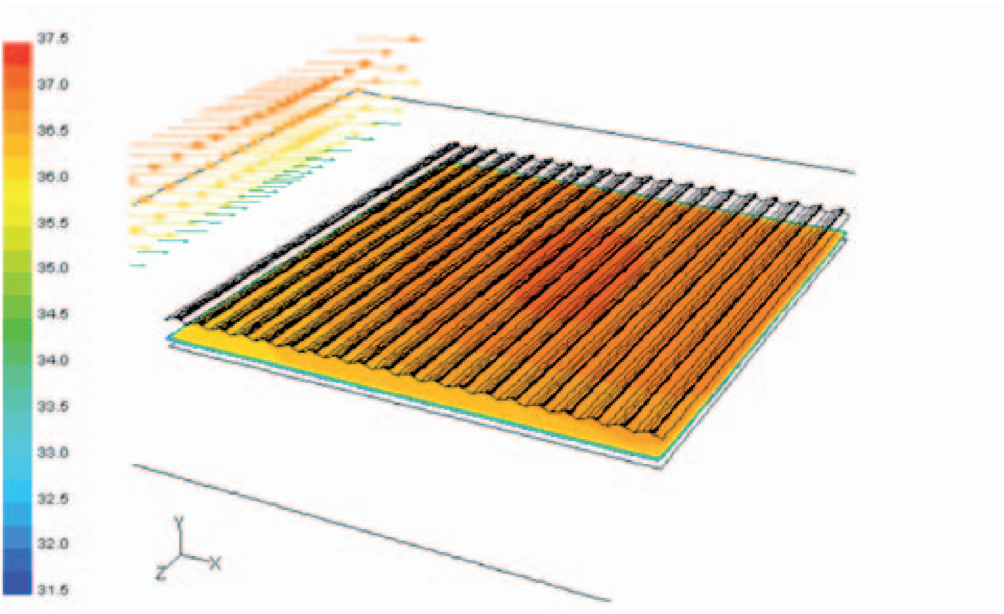


Figure 4.20 Air temperature distribution in a greenhouse with span width 9.6 m equipped with insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 35.90 °C, max air temp: 37.05 °C, difference air temp: 1.15 °C, ventilation rate: 53.1 $m^3 m^{-2} h^{-1}$, air changes per hour: 8.16)

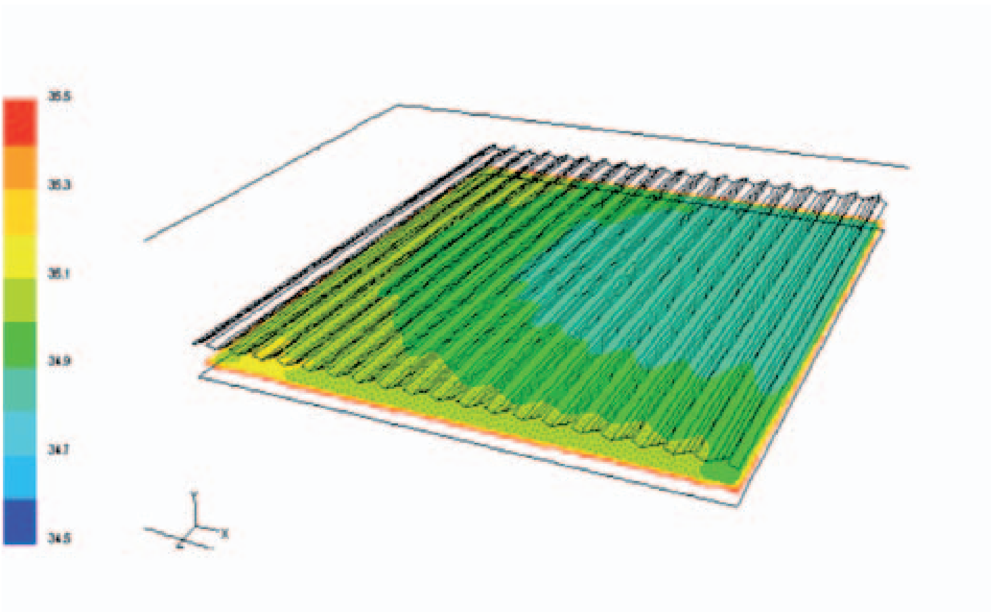


Figure 4.21 Air temperature distribution in a greenhouse with span width 9.6 m equipped with fogging system (capacity 500 g $m^{-2} h^{-1}$), in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 34.2 °C, max air temp: 35.1 °C, difference air temp: 0.8 °C)

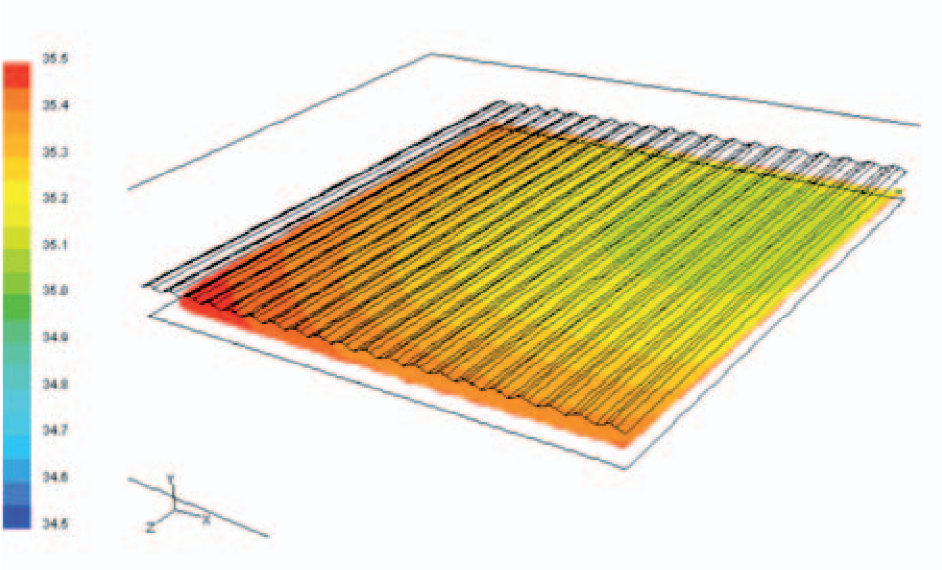


Figure 4.22 Air temperature distribution in a greenhouse with span width 9.6 m equipped with fogging system (capacity 300 g m^{-2} h^{-1}) and NIR screen, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 34.5 °C, max air temp: 35.4 °C, difference air temp: 0.9 °C)

4.3.4 Influence of recirculation fans to greenhouse microclimate

The influence of recirculation fans to the inside air temperature distribution was investigated by simulating a 1 ha Venlo type greenhouse equipped with 72 fans (TB4E40Q). The recirculation fans cause an increase of air velocity above the canopy (Figure 4.23) and one might think that this has a positive effect to the air temperature distribution in the cop level. However this argument is not valid since the operation of recirculation fan has a negative effect to the uniformity of the environment, (Figure 4.24). Next to that, the operation of recirculation fans increases the use of electricity in the greenhouse. The use of recirculation fans can not be recommended.

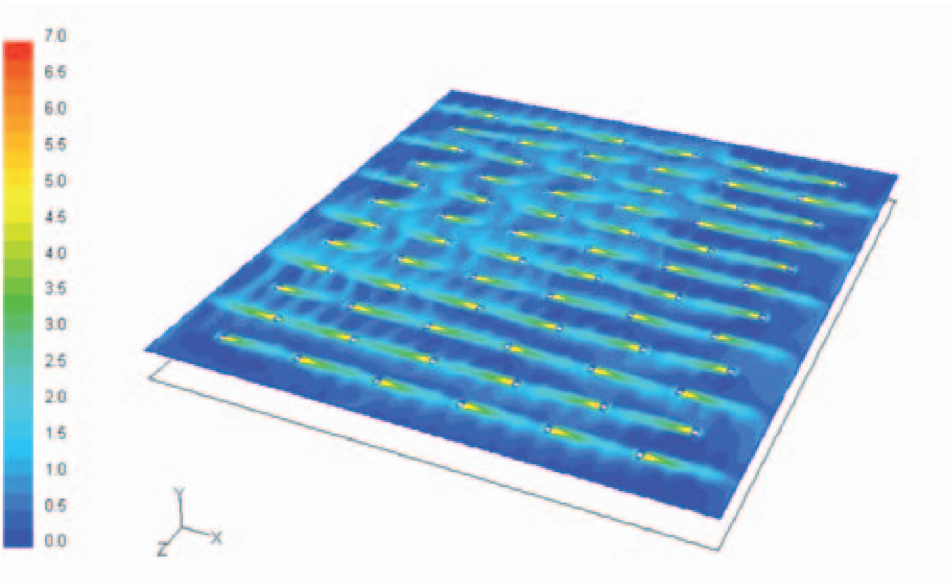


Figure 4.23 Air velocity distribution in a greenhouse with span width 9.6 m equipped with 72 recirculation fans, in a horizontal cross plane surface at 5.6 m above the ground

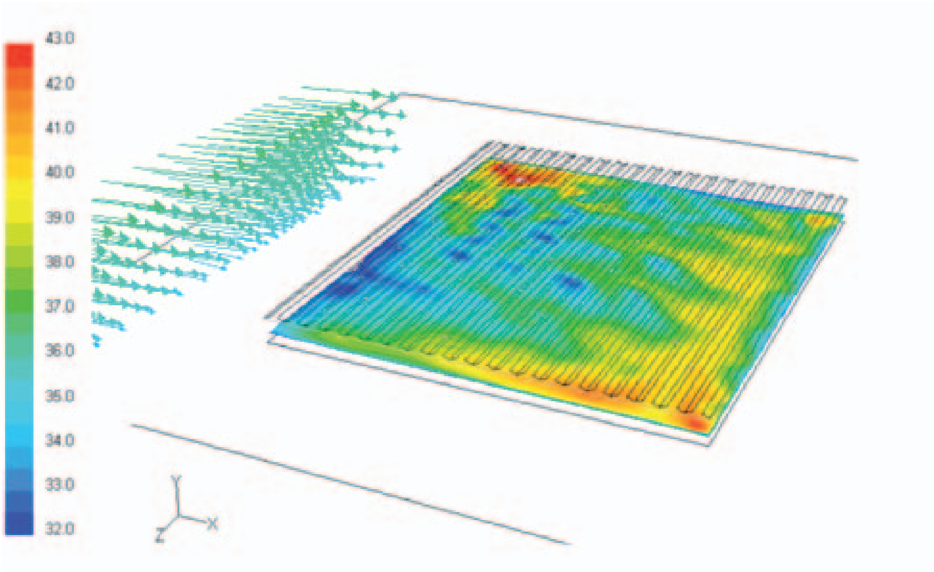


Figure 4.24 Air temperature distribution in a greenhouse with span width 9.6 m equipped with 72 recirculation fans, in a horizontal cross plane surface at 2.0 m above the ground, (average air temp. at crop level: with fans 36.8 °C, without fans 36.4 °C, air temp. difference at crop level: with fans 9.3 °C, without fans 5.9 °C)

4.3.5 Influence of natural ventilation to CO_2 distribution

It is well know that the optimal use of the available amount of CO_2 positively affected crop production (Dieleman *et al.*, 2006). Is has also been shown, from the computational results presented here above, that insect nets have a positive effect to air temperature uniformity. The influence of insect nets to CO_2 distribution was investigated by simulating a 1 ha Venlo type greenhouse with and without insect nets. The calculations were performed assuming CO_2 absorption rate of 0.008 kg m^{-2} h^{-1} and release rate 0.012 kg m^{-2} h^{-1} (aiming a level of 700 ppm). The results show that the greenhouse with insect nets has 17% more CO_2 concentration than the greenhouse without, (Figures 4.25 & 4.26), which confirms the recommendation for the use of insect nets combined with the application of CO_2.

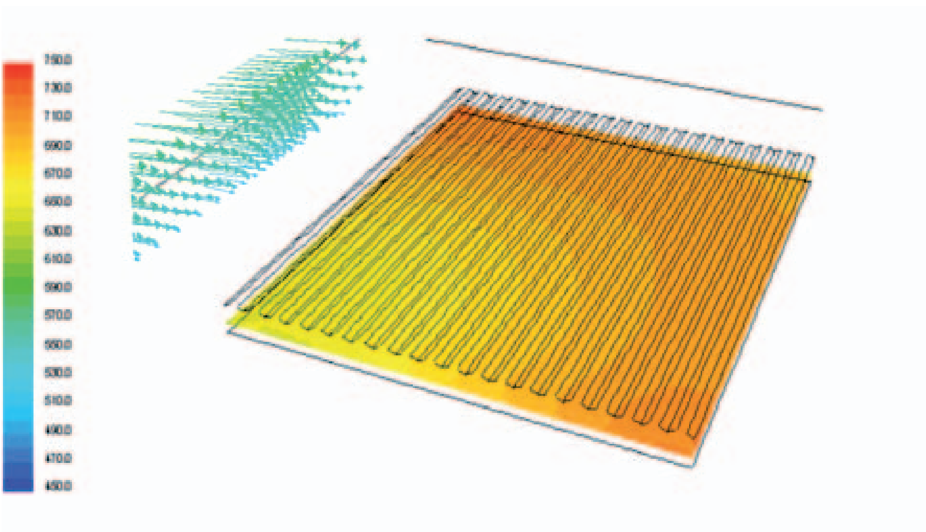


Figure 4.25 CO_2 distribution in a greenhouse with span width 9.6 m equipped with insect nets, (average concentration of CO_2: 690.5 ppm, range: 635-725 ppm)

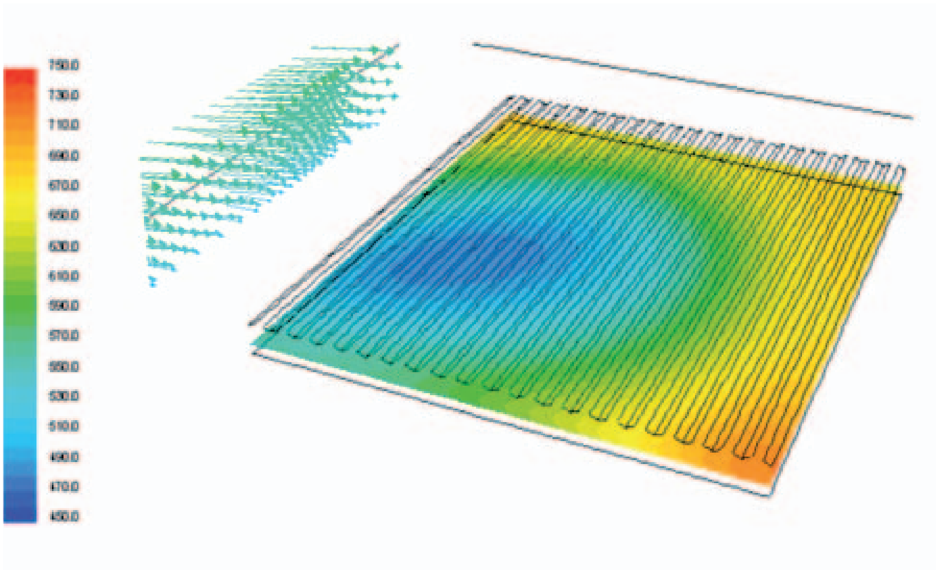


Figure 4.26 CO_2 distribution in a greenhouse with span width 9.6 m without insect nets, (average concentration of CO_2: 590.3 ppm, range: 482-715 ppm)

4.3.6 Influence of the size of the greenhouse

As all the calculations till now have been done considering a 1 ha Venlo type greenhouse, the question which arise is which is the influence of the size of the greenhouse to the distributed climatic variables, mainly to temperature. By using the same boundary conditions and the same grid quality, two simulations models with different design were solved, (1 ha and 2 ha). The results show that the air temperature inside the greenhouse with area 2 ha was 2% more than the greenhouse with area 1 ha and the ventilation rate was 5% less, (Figures 4.27 & 4.28). With this order of magnitude differences the solution is size independent regarding greenhouses 1 ha or 2 ha.

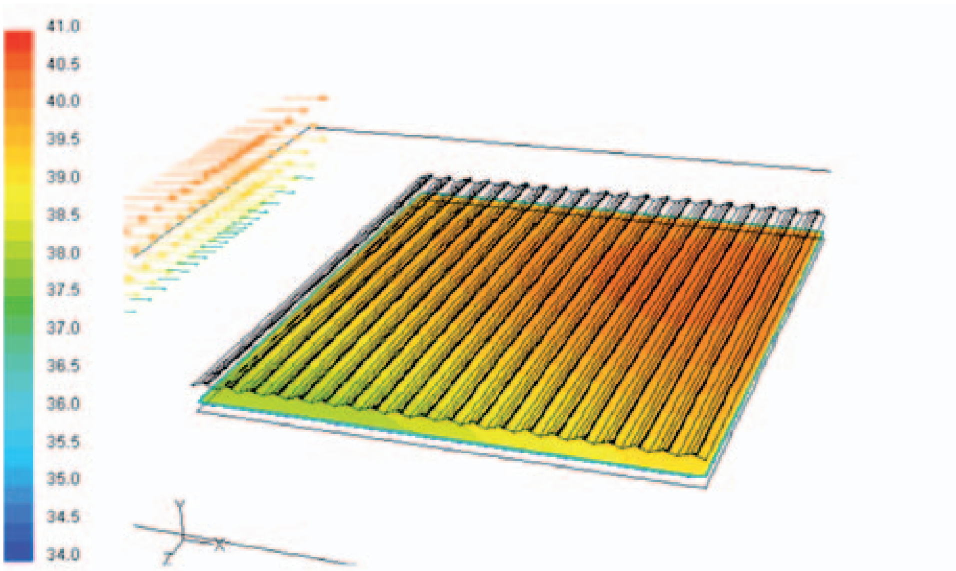


Figure 4.27 Air temperature distribution in an 1 ha greenhouse with span width 9.6 m equipped with insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 10°, min air temp: 38.1 °C, max air temp: 39.7 °C, ventilation rate: 59.8 m^3 m^{-2} h^{-1}, air changes per hour: 9.2)

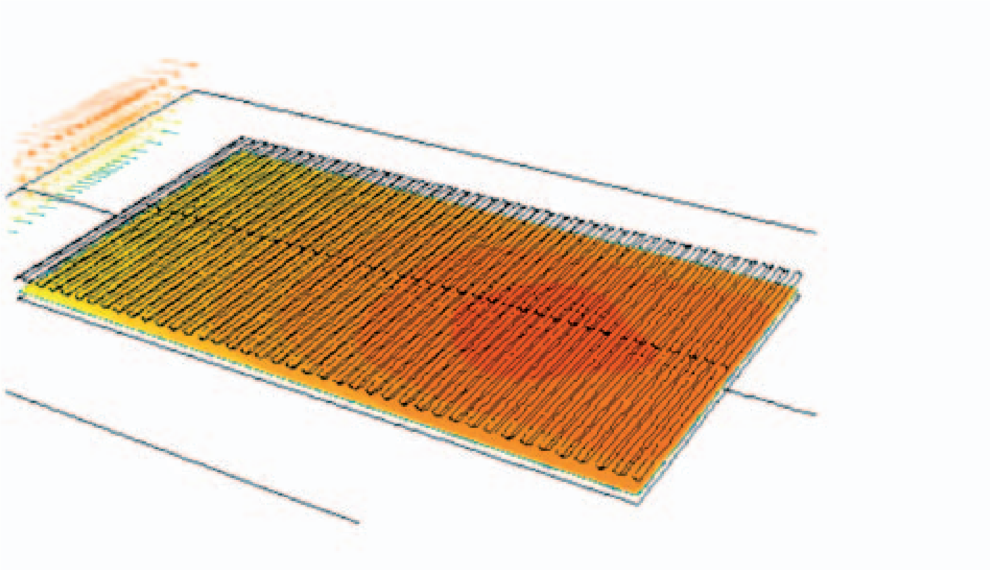


Figure 4.28 Air temperature distribution in an 2 ha greenhouse with span width 9.6 m equipped with insect nets, in a horizontal cross plane surface at 2.0 m above the ground, (wind speed 1 m s^{-1} and wind direction 0°, min air temp: 38.7 °C, max air temp: 40.6 °C, ventilation rate: 56.7 m^3 m^{-2} h^{-1}, air changes per hour: 8.7)

4.3.7 Conclusions obtained by CFD study

CFD calculations were performed in order to obtain additional information for the optimum design of a Sustainable innovation greenhouse for the Western part of Turkey. The calculations were carried out regarding a 1 ha Venlo type greenhouse in order to investigate the influence of different design and system parameters to greenhouse microclimate. The following conclusions can be drawn from the CFD study:

- The ventilation performance of a Venlo type greenhouse with span with 8.0 m is better than the performance of similar greenhouse with span width 9.6 m due the more uniform distribution of the openings for the same area of greenhouse, but the differences are not so big to justify the adoption of this design.

- The ventilation rate of a greenhouse under Western Turkey conditions mainly is influenced by the temperature differences rather than wind speed. At high wind speeds the positive influence to the air temperature, of decreasing the span width from 9.6 to 8.0 m is small.

- Wind direction has small influence to the ventilation rate (lower if perpendicular to the ridge) and this effect expected to be smaller in bigger greenhouses (more than 1 ha).

- Using side openings equipped with insect nets increases the ventilation rate. The average air temperature is lower but the uniformity is worse.

- Using antithrips insect nets has negative effect to the ventilation rate. The average temperature is higher, especially the minimum air temperature increases. However, adding additional cooling methods like fogging and/or shading to a greenhouse with insect netting in the vents prevents unfavourable high temperatures.

- Using insect nets has positive effect to the air temperature distribution. The differences are at the order of 2-3°C while without nets are at the order of 5-8 °C.

- Using insect nets has positive effect to the CO_2 distribution. For the same weather conditions, the average CO_2 concentration was 17% higher. The uniformity is also better as the difference between min and max values of concentration is 2.5 times more in a greenhouse without insect nets. The positive effect will be higher when higher wind speeds are occurred.

- If fogging system is applied the air temperature is low enough also during the application of antithrips nets and the uniformity is also good.

- Using internal shading net of 30% decreases the average temperature level but it remains higher than applying fogging at the order of 3-4 °C. Next to that it will reduce crop photosynthesis when the screen is closed.

- A combination of NIR reflecting screen and fogging system with capacity of 300 g m^2 h^{-1} could provide acceptable climatic conditions even under extremely warm outside conditions, (air temperature: 38 °C and solar radiation: 1100 W m^{-2}). Due to economic reasons the NIR reflecting screen can not be recommended.

- A high capacity fogging system will provide acceptable climatic conditions under extremely warm outside conditions.

- Using recirculation fans has almost no effect regarding the average air temperature inside the greenhouse even if the air flow velocities are increased above the crop. Recirculation fans might have a negative effect on the uniformity of the environment especially at high wind speeds and with high fluctuations of wind direction.

- By doubling the size of the greenhouse from 1 ha to 2 ha the air temperature in the crop level is increased about 2% and the ventilation is decreased about 5%. At this order of magnitude, the results are size independent and reliable to be used for future studies.

- CFD is a powerful tool to compare different heating/cooling commercial systems for specific conditions in qualitatively and quantitatively terms.

4.4 Results of the economic model

In an economic quick-scan several scenario's concerning different degrees of technology are analyzed in order to determine the optimum greenhouse design for the Western part of Turkey and to decide the right configuration of the Sustainable Innovation greenhouse to be built in that area. Glass and plastic film greenhouses are compared. Next to that, an increasing degree of technology is analyzed: with heating, with cooling by fogging, with the application of CO_2, open vs. closed water system, and artificial lighting. Finally the economic result of the chosen combination of technologies is given.

Table 4.6 Benefit, costs and investments for different greenhouse designs with different degrees of technology, annual balance of benefits and costs and payback period resulting from the economic model

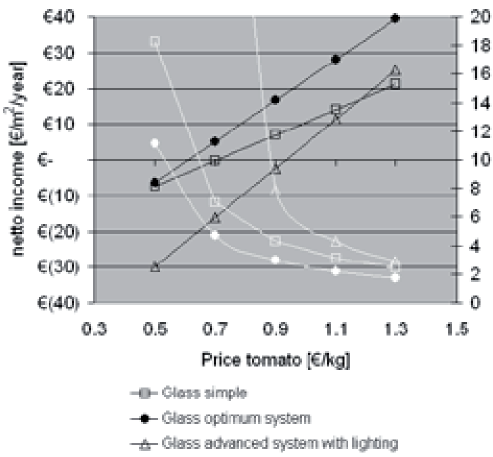
	Glass standard	Glass with CO_2	Glass with fogging	Glass with CO_2 & fogging	Glass with CO_2 & fogging & closed water system	Glass CO_2 & fogging & closed water system & lighting	Glass with CO_2 & fogging & closed water system, insect nets & screens
payback period (simple method) [years]	4.3	3.0	4.4	3.0	3.1	7.9	3.0
investment 1 ha greenhouse [k€/ha]	k€816,8	k€837,8	k€846,8	k€872,8	k€892,8	k€1292,8	k€939,8
production [kg/m²/year]	36.0	53.3	36.4	54.7	54.7	68.9	57.5
price tomato [€/kg]	€ 0.90	€ 0.90	€ 0.90	€ 0.90	€ 0.90	€ 0.90	€ 0.90
total income crop [€/m²/year]	*€ 32.40*	*€ 47.95*	*€ 32.72*	*€ 49.25*	*€ 49.25*	*€ 62.05*	*€ 51.71*
energy (& CO_2) [€/m²/year]	€ 3.47	€ 9.56	€ 3.47	€ 9.56	€ 9.56	€ 33.54	€ 9.56
Labor [€/m²/year]	€ 2.25	€ 2.86	€ 2.26	€ 2.91	€ 2.91	€ 3.42	€ 3.01
water & nutrients (& recirculation) [€/m²/year]	€ 1.27	€ 1.27	€ 1.27	€ 1.27	€ 0.91	€ 0.91	€ 0.91
others (chemicals, substrate, packaging etc.) [€/m²/year]	€ 4.91	€ 5.08	€ 4.91	€ 5.10	€ 5.10	€ 5.24	€ 4.92
total variable costs [€/m²/year]	*€ 11.90*	*€ 18.78*	*€ 11.92*	*€ 18.84*	*€ 18.48*	*€ 43.11*	*€ 18.40*
greenhouse construction & covering [€/m²]	€ 35.00	€ 35.00	€ 35.00	€ 35.00	€ 35.00	€ 35.00	€ 35.00
change covering [€/m²]	€-	€-	€-	€-	€-	€-	€-
other installation costs (heating, CO_2, screening, climate control etc.) [€/m²]	€ 27.20	€ 29.30	€ 30.20	€ 32.80	€ 34.80	€ 74.80	€ 39.50
additional installation costs (transport, packaging area, machinery etc.) [€/m²]	€ 19.48	€ 19.48	€ 19.48	€ 19.48	€ 19.48	€ 19.48	€ 19.48
total installation costs incl. depreciation, maintenance, interest [€/m²/year]	€ 13.60	€ 14.30	€ 14.06	€ 14.84	€ 15.15	€ 21.35	€ 16.73
financial result [€/m²/year]	*€ 6.90*	*€ 14.87*	*€ 6.74*	*€ 15.56*	*€ 15.62*	*€ (2.40)*	*€ 16.58*

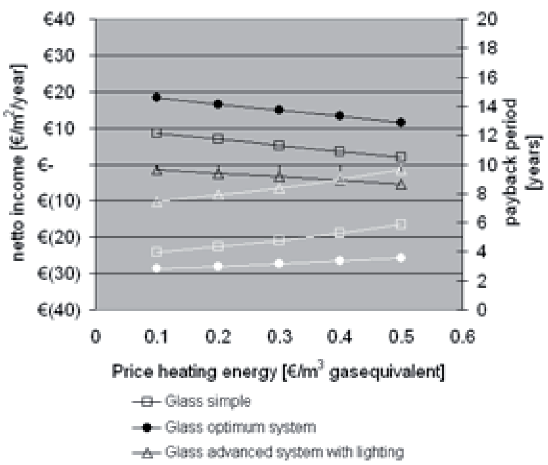
	Turkish plastic standard	Plastic standard	Plastic with CO_2	Plastic with fogging	Plastic with CO_2 & fogging	Plastic with CO_2 & fogging & closed water system
payback period (simple method) [years]	6.2	4.4	3.0	4.6	3.0	3.1
investment 1 ha greenhouse [€/ha]	k€516,1	k€784,8	k€805,8	k€814,80	k€840,8	k€860,8
production [kg/m²/year]	25.0	36.7	54.4	36.7	55.4	55.4
price tomato [€/kg]	€ 0.90	€ 0.90	€ 0.90	€ 0.90	€ 0.90	€ 0.90
total income crop [€/m²/year]	*€ 22.50*	*€ 33.05*	*€ 48.92*	*€ 33.05*	*€ 49.90*	*€ 49.90*
energy (& CO_2) [€/m²/year]	€ 5.21	€ 5.21	€ 11.16	€ 5.09	€ 11.16	€ 11.16
labor [€/m²/year]	€ 1.86	€ 2.27	€ 2.90	€ 2.27	€ 2.94	€ 2.94
water & nutrients (& recirculation) [€/m²/year]	€ 1.27	€ 1.27	€ 1.27	€ 1.27	€ 1.27	€ 0.91
others (chemicals, substrate, packaging etc.) [€/m²/year]	€ 4.80	€ 4.92	€ 5.09	€ 4.92	€ 5.10	€ 5.10
total variable costs [€/m²/year]	*€ 13.14*	*€ 13.68*	*€ 20.43*	*€ 13.56*	*€ 20.48*	*€ 20.12*
greenhouse construction & covering [€/m²]	€ 18.00	€ 30.00	€ 30.00	€ 30.00	€ 30.00	€ 30.00
change covering [€/m²]	€ 6.75	€ 6.75	€ 6.75	€ 6.75	€ 6.75	€ 6.75
other installation costs (heating, CO_2, screening, climate control etc.) [€/m²]	€ 17.20	€ 27.20	€ 29.30	€ 30.20	€ 32.80	€ 34.80
additional installation costs (transport, packaging area, machinery etc.) [€/m²]	€ 14.61	€ 19.48	€ 19.48	€ 19.48	€ 19.48	€ 19.48
total installation costs incl. depreciation, maintenance, interest [€/m²/year]	*€ 8.32*	*€ 13.42*	*€ 14.13*	*€ 13.89*	*€ 14.67*	*€ 14.98*
net income [€/m²/year]	*€ 1.03*	*€ 5.95*	*€ 14.37*	*€ 5.60*	*€ 14.75*	*€ 14.80*

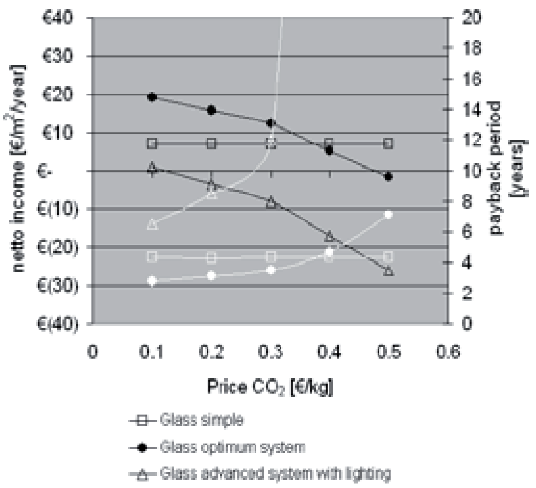
From these results it can be concluded that with adding the right technology more income can be generated with the greenhouse production, compared to a simple greenhouse (glass standard or plastic standard or the traditional Turkish plastic greenhouse). Adding CO_2 to a heated greenhouse improves both the yearly income and the payback period due to a high yield increase. Adding additionally fogging improves the result further due to a better humidity and temperature control. The optimum greenhouse system has been identified to be with CO_2 application, fogging, closed water system, insect screens, and energy screens. In economical terms the income generated with that greenhouse, only improves slightly. However, it can be recommended to add more technology in order to make the greenhouse more sustainable (closed water cycle, less pesticides due to insect screens, less energy due to energy screens) and to make production year-round more reliable (fogging, screens) even though the economic result does not improve linearly with the higher investments. In case of using more technology it is, however, absolutely necessary to have skilled people operating the greenhouse. A high level of training and education is necessary to get optimum results.

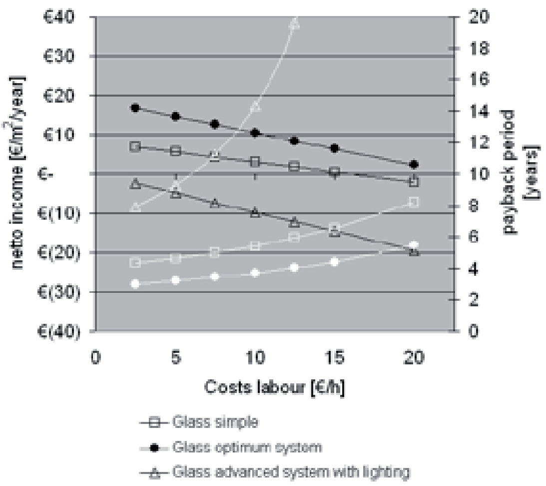
When a plastic film greenhouse is economically compared with a glass greenhouse, often the expectations are that this greenhouse is much cheaper and therefore has a much higher economic benefit. However, in the calculations it can be seen that this is only partly true, since costs for energy consumption are higher due to the higher heat losses of the greenhouse. These costs are overruling the advantages of lower day temperatures during hot periods. Due to some other arguments like light losses of a plastic film due to ageing and more difficult cleaning and due to the higher labour costs due to changing of the covering after 3-4 years, the project group has chosen for a glass greenhouse for the Sustainable innovation greenhouse in Turkey.
It can be expected that the yearly financial result of the optimized greenhouse is higher than the financial result generated in a traditional Turkish plastic film greenhouse, though the initial investment is more than 1.5 times higher.

The results of the sensitivity analysis is shown in the figures here below, where prices for the produce, for energy and CO_2 are varied as well as costs for labour, greenhouse construction and installations and the interest rate in Turkey. In all the figures variations are given for the simple glass greenhouse compared to the optimum glass greenhouse with CO_2 application, fogging, closed water system, insect screens, and energy screens and compared to the advanced glass greenhouse with artificial lighting.









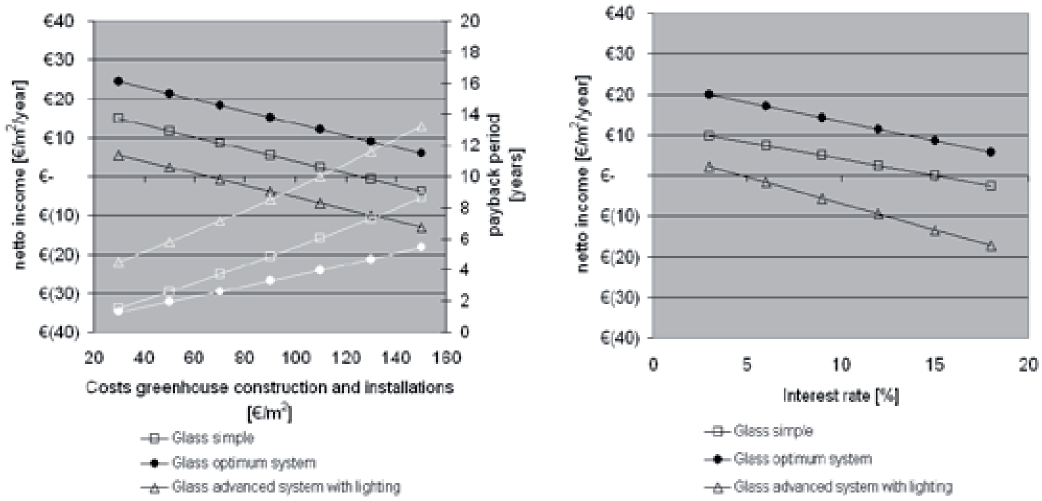


Figure 4.29 Sensitivity analysis

From the figures it can be concluded that the financial result is strongly dependent on the price for the produce, in this case tomato. By the way, the dependence is lower in case of the optimum greenhouse. The price for the produce is also strongly influencing the payback period. In case of the optimum greenhouse an average price of €0.70 per kg tomato is needed to achieve a pay back time of the investment of less than 5 years and to reach a positive annual net income. A price of €1.10 per kg tomato or higher would be needed in order to get a positive result of the artificial lighting. However, very much higher prices are needed in order to get a better result than in the optimum greenhouse configuration.

The influence of the energy prices on the annual financial result and the payback period is limited. So is the influence of the labour costs. If the price of CO_2 is less than €0.40 per kg application improves the economic result of the optimum system compared to the standard. The initial investment for greenhouse construction and installation is smaller than the influence of product price. In the case of the optimum greenhouse system the pay time will remain lower than 5 years up to initial investments of €150 per m^2 in case of product prices of €0.90 per kg tomato year-round. In case seasonal changes in tomato product prices are expected high investment costs are more risky than low investment costs. In case investors have to get a loan from the bank the interest rate is important. In case of the optimum greenhouse system interest rates should be below 20%. Historical data of the interest rates in Turkey show that it was below 20% for the last 5 years, it especially decreased the last 6 months down to a value of currently 6.5%, the value used for the calculations here.

From this sensitivity analysis we can conclude that it is of high importance that high product prices are achieved on the market in order to get a reliable positive net income. Product prices form the major risk for investors to reach a short payback time.

4.5 Indicators for sustainability

Several indicators for sustainability are calculated in order to evaluate the different greenhouse systems with different degree of technology. The indicators for sustainability are summarized in the tables below.

Table 4.7 Indicators for sustainability

	Glass standard	Glass with CO_2	Glass with fogging	Glass with CO_2 & fogging	Glass with CO_2 & fogging & closed water system	Glass CO_2 & fogging & closed water system & lighting	Glass with CO_2 & fogging & closed water system & insect nets & screens
Use of resources:							
Water consumption [kg produce/m^3]	28.3	41.8	27.1	38.4	49.4	62.3	51.9
Energy (heat) consumption [MJ/kg]	14.7	9.9	14.5	9.7	9.7	4.5	9.2
Produce less environmental loads:							
CO_2 application per unit produce	zero	high	zero	medium	medium	high	medium
Nutrient emissions	high	high	high	high	low	low	low
Pesticides applied per unit produce	high	high	high	medium	medium	medium	low
Efficiency of production process:							
Yield per area [kg/m^2]	36.0	53.3	36.4	54.7	54.7	68.9	57.5
Profit per area and year [€/m^2/year]	€6.90	€14.87	€6.74	€15.56	€15.62	€(2.40)	€16.58
Payback period [years]	4.3	3.0	4.4	3.0	3.1	7.9	3.0

	Turkish plastic standard	Plastic standard	Plastic with CO_2	Plastic with fogging	Plastic with CO_2 & fogging	Plastic with CO_2 & fogging & closed water system
Use of resources:						
Water consumption [kg produce/m^3]	27.5	30.5	53.0	25.1	37.8	53.0
Energy (heat) consumption [MJ/kg]	32.2	21.9	14.4	21.4	14.2	14.2
Produce less environmental loads:						
CO_2 application per unit produce	zero	zero	high	zero	medium	medium
Nutrient emissions	high	high	high	high	high	high
Pesticides applied per unit produce	high	high	high	high	medium	medium
Efficiency of production process:						
Yield per area [kg/m^2]	25.0	36.7	54.4	36.7	55.4	55.4
Profit per area and year [€/m^2/year]	€1.03	€5.95	€14.37	€5.60	€14.75	€14.80
Payback period [years]	6.2	4.4	3.0	4.6	3.0	3.1

From these tables it can be concluded that the water consumption per unit produce is highest in the traditional Turkish plastic film greenhouse, here expressed has unit produce per unit water. The water consumption is lowest in the most advanced greenhouse with artificial lighting, due to the high production and high degree of technology. For the cases of the optimum greenhouse system and all other systems with closed water system the water consumption is also low. It can be stated that fogging increases water consumption; however, since crop transpiration is also lowered and crop yield is increased the water consumption per unit product is still low.

The highest heat energy consumption per unit produce can be found in the simple Turkish plastic greenhouse and all other plastic film greenhouse systems, due to the high radiative heat losses through the covering material since plastic transmits long wave heat radiation whereas glass does not. In case of the advanced greenhouse system with artificial lighting the heat energy consumption seems to be lowest. However, in the table it is not taken into account that a large amount of electrical energy is consumed by the lighting system which is converted in heat energy consumed by the system. So the lowest heat energy consumption can be found in optimum greenhouse system.

The environmental impact of the different systems can only be estimated in a qualitative way. In cases when no CO_2 is applied, of course the environmental impact of CO_2 emission out of the greenhouse is zero, in cases when fogging and insect nets are applied CO_2 emission from the greenhouse is lower, since ventilation rates are lower compared to traditional systems. Also the impact of nutrient emission can only qualitatively be estimated. Closed irrigation systems show much lower nutrient emissions. However, all soilless culture systems have already lower impact than soil grown systems. The amount pesticides applied will be strongly related to hygienic and the pest and disease pressure in the surrounding rather than to the greenhouse system itself. However, it can be expected than pests will be reduced by insect nets and disease will be reduced due to better growing conditions due to higher degree of technology applied. It is strongly recommended to monitor the environmental impact of the once realized Sustainable innovation greenhouse by practical measurements in order to get quantitative values for the environmental impact of the system.

4.6 Description of optimum greenhouse design for Western Turkey – the system

In this chapter the optimum system for the Sustainable innovation greenhouse is described. The Sustainable innovation greenhouse has a size of 1.5 ha and is suitable for tomato crop production. The technical system consists of a Venlo-type greenhouse with continuous roof ventilation. A span width of 8 m should be preferred above a span width of 9.6 m due to the slightly higher ventilation capacity. The greenhouse will be equipped with a heating system and heat exchanger based on a geothermal well with sufficient amount of water at high temperatures (ca. 90 ºC). The heat from the geothermal well will first be used in the energy plant to produce electricity; the waste heat will then be used to heat greenhouses before it will be re-injected again in the ground. The project group has chosen to apply hanging gutters. The use of CO_2 is of great importance for a viable greenhouse crop. CO_2 can either be obtained as liquid CO_2 from domestic sources or ideally it could be obtained from the geothermal well. A horizontal energy screen system will be installed in order to increase energy efficiency, have better temperature distributions in winter time on half of the area. An aluminized energy cloth will chose with maximum energy saving on half of the greenhouse area. During summer time the aluminized energy screen will not be used. On the other half of the area a traditional combination screen will be installed, with 30% shading, which can also be used during summer time and gives less energy saving during winter time. All vents will be equipped with an anti-thrips insect netting system.

A closed irrigation system will be installed in order to save water and minimize nutrient emissions. The drain from the irrigation system will be collected and stored and sterilized with heat preferable. For heat sterilization the heat from the geothermal well can be used. To enable humidity control as well as control of summer temperatures, a medium pressure fogging system will be installed. The control of excessive heat in summer will be done by this fogging system and the high ventilation capacity through the continuous roof ventilation.

The greenhouse climate control will be done automatically by a greenhouse climate computer, which automatically controls heating, ventilation, fogging, CO_2 application, screen opening and water and nutrient application due to the given setpoints. Within the system the crop will be planted at the end of July or the beginning of August and ended at the end of June. Locally produced organic substrate (sustainable, no waste) will be used.

It is chosen for this greenhouse concept as a result of the dynamic climate calculations showed in chapter 4.2, the additional results of the CFD calculations showed in chapter 4.3 and the indicators of sustainability shown in chapter 4.5. Last but not least, the results of the economic quick scan in chapter 4.4. show that this combination of technology result the shortest payback period combined with a low risk for the investment.

5 Organizational and juridical aspects of the Sustainable Innovation Greenhouse

In order to realize a Sustainable innovation greenhouse in Turkey and to show Dutch technology, expertise and knowledge, the co-operation of a Turkish partner is needed. For that the best location in Turkey had to be chosen and a partner had to be selected.

The project group decided to focus with the realization of the Sustainable innovation greenhouse on the Western part of Turkey, since:
- The focus of large investors lays on the Western part of Turkey.
- The region in the Western part of Turkey is developing fast concerning horticultural activities.
- Geothermal sources are available in the Western region.
- The climate in Western Turkey is favourable for horticultural production in greenhouses.

The project group further focused on a Turkish partner outside the traditional horticultural circuit. Large energy companies or large agricultural co-operations are preferred. The following criteria were defined in order to select a proper Turkish partner and location:
- commitment of the partner (financially and organizational);
- ability to create commitment towards other Turkish parties like governmental authorities, horticultural supply industry and growers;
- degree of independence of partner;
- availability of sustainable energy sources (geothermal sources);
- possible scale (horticultural area with other large growers);
- state of the art technology (horticultural area with other modern greenhouses);
- availability of infrastructure;
- knowledge.

The realization of the Sustainable innovation greenhouse is not only important to demonstrate Dutch technology, expertise and knowledge but it has also several advantages for the Turkish investors:
- Sustainable collaboration with Dutch industry - unique combination of technology, knowledge and education.
- Optimum design for Turkish situation.
- Reliable Dutch technology.
- Demonstrate that and how economical beneficial production is possible by using heat, electricity and CO_2 from geothermal source.
- Make benefit directly with the innovation greenhouse.
- Attract other investors.

During the project period the project group was able to find a suitable investment partner and signed a letter of intent with that partner. Currently the contract negotiations are ongoing. If everything is going well the Sustainable innovation greenhouse can be built in 2010.

6 Future activities and knowledge transfer planned within the Sustainable Innovation Greenhouse

Objective of this project was to identify the optimum greenhouse design for Western Turkey. A potential Turkish partner and location has been found. It is estimated that the Sustainable innovation greenhouse could be realized in 2010. Therefore it is important to define the future activities and knowledge transfer for the future. A rough planning for that has been made concerning:

- The physical realization of the greenhouse.
- The management of the greenhouse.
- The demonstration and monitoring activities we want to employ.
- The communication activities linked to greenhouse.

The physical realization of the greenhouse can be described as follows: The greenhouse will be 1.5 ha, visitors will be able to look into the greenhouse via a transparent corridor. There needs to be a visitor's room with permanent information about the innovation greenhouse itself, the consortium realizing the innovation greenhouse, information about SeraCulture in general, the companies and their expertise, know-how and products. Next to that a meeting room is necessary to organize workshops and other activities.

In principle the investor is owner of the Sustainable innovation greenhouse. Next to that a Dutch manager will be hired to run the Sustainable innovation greenhouse for a period of 3 years. He will manage the greenhouse daily and will have several trained Turkish workers at his side. The training of the manager and the workers will be needed to be done before the start of the first crop in the innovation greenhouse in The Netherlands. Next to that training on the job will regularly take place in Turkey. An additional EVD project plan is already submitted for that.

The following demonstration and monitoring activities will be needed in the Sustainable innovation greenhouse:

- Demonstration of Dutch technology and cropping systems.
- Development of new greenhouse climate, cropping and integrated pest management strategies specific for Turkish conditions.
- Knowledge transfer (Workshops) to inform farm managers and other relevant interested parties in the Turkish horticultural sector: 4 times a year, invite Turkish growers, supply industry, investors, local authorities, chamber of commerce, different topics *e.g.* greenhouse design, integrated pest management, water, greenhouse climate, marketing, sales, organize together with NABSO and Dutch company relations.
- SeraCulture members show the Sustainable innovation greenhouse to their (potential) clients, show their expertise and products in demonstration room.
- The innovation greenhouse is especially designed within this project. The optimum greenhouse design should lead to a most economically beneficial benefit and a high quality production. The real economic figures and sustainability indicators have to be collected in the practical greenhouse. Data related to crop growth and production (harvest, fruit weight, size, quality), dynamic greenhouse climate (temperature, humidity, CO_2 concentration, light), homogeneity of greenhouse climate, water consumption, energy consumption, CO_2, nutrient and chemical emission have to be collected. The real data should be published regularly on the website and a newsletter to relevant parties.
- Collaboration with a Turkish university in order to increase the knowledge level in Turkey and to collect as much as possible information within the Sustainable innovation greenhouse. A PhD student is suggested to contribute to the evaluation of the Sustainable innovation greenhouse.

It is strongly recommended to pay high attention to the future activities and knowledge-transfer described above once the Sustainable innovation greenhouse is realised.

7 Conclusions

A design for a Sustainable Innovation Greenhouse for the Western part of Turkey has been made within this project. Turkish investors have been found in order to build a Sustainable Innovation Greenhouse with Dutch knowledge and technology. A greenhouse design should always be adapted to local climatic and socio-economic conditions. Within this project special attention has also be given to several sustainability factors.
A specific design methodology was followed. Different degrees of greenhouse technology have been investigated and analysed with different technical and economical models in order to find the optimum sustainable and economic feasible solution for Western Turkey. The following conclusions can be summarised:

- The climate in the Western part of Turkey can be characterized by low temperatures in winter (heating needed), high/moderate temperatures in summer (cooling needed) and high natural light levels, even in winter (no artificial light needed). The climate is favourable for greenhouse tomato crop production if the right technology is used.

- Heating will be applied by geothermal energy on location. Electricity will be made from a geothermal power plant. CO_2 can be extracted from the geothermal well too.

- Natural ventilation by continuous roof ventilation is an efficient basic method of cooling. Fogging is advised as additional cooling method, next to that higher humidity levels and less crop stress result, especially when the crop is young.

- Recirculation fans do not increase temperature homogeneity and therefore do not contribute to better summer conditioning of the greenhouse.

- CO_2 increases crop production potentially with about 38%. Application of CO_2 is advisable.

- The application of an energy saving screen is recommended from a sustainable point of view. Two strategies should be tried in praxis: a. highly aluminized tight screen for maximum energy saving in winter, solar energy control during summer only by natural ventilation and fogging (new), b. combination screen with less energy saving but for additional light and solar energy input control during summer (common practice).

- Additional light control for production increase could be done by applying artificial lighting, which would increase the production with about 26%. From an economical point of view that cannot be recommended.

- The application of insect nets (anti-thrips) is recommended in order to potentially save pesticides. CFD calculations have shown that the application of insect nets is possible without increasing inside greenhouse temperature too much if additionally fogging is applied. Insect nets improve temperature distribution inside the greenhouse. Insect nets improve CO_2 distribution and CO_2 concentration.

- Crops will be grown soilless on a preferably local biodegradable substrate. Water will be recycled and disinfected by geothermal heat. The water use efficiency will be very high.

- From an economic point of view a greenhouse with only heating and CO_2 application gives high yields and a short payback period. Adding more technology like fogging, shading and insect nets increases the certainty of production and decreases the risk of production or quality losses. On the other hand, adding more technology increases investment costs and therefore the financial risk for investors in case of low product prices on the market. The payback period of a system with more technology is comparable to the more simple system. However, the optimum greenhouse design with more technology can be recommended since only that way product quality and supply continuity can be assured. The optimum greenhouse design suggested here will increase the yearly income of Turkish horticultural farmers. Next to that the production period during summer can be increased. Such a system requires skilled people and a high level of education and training, though.

- Economic results are strongly dependent on product prices. Investment, energy, CO_2 and labour costs are of minor influence for the optimum solution, whereas interest rates in Turkey are important.

- From a sustainable point of view the use of geothermal energy gives important possibilities for Western Turkey. The optimum greenhouse design suggested here gives highest water efficiency, high possibilities for saving pesticides and lowest emissions. It will certainly improve the sustainability of Turkish horticulture. Quantification of indicators of sustainability will be needed by practical data collection in the real greenhouse.

- The greenhouse concept was chosen based on a good design methodology and the use of different model calculations and decision support systems as well as an economic model. That is an efficient way of designing new greenhouse concepts.

- A thorough evaluation of technical, economical and sustainable parameters of the Sustainable Innovation Greenhouse by practical measurements and data collection in the future is highly recommended.

- Other future activities are knowledge transfer and a well thought-out communication strategy with Turkish stakeholders in order to make the project economically successful for the Dutch SeraCulture companies.

8 Summary

In scope of the program 2g@there in May 2008 an agreement was signed between EZ (EVD), LNV, AVAG, VRIAN and WUR. Turkish private investors and the local and central government were approached in 2008. The goal of the program 2g@there is to increase the favourable position of Dutch technology suppliers and horticultural related business in Turkey and create sustainable and fruitful relationship between both. An activity in the program is establishing an innovative greenhouse and knowledge centre in one of the regions of Izmir/Aydin/Dikili, Burza, Antalya or Ankara. The innovative greenhouse will be designed specially to realize an environmental friendly and sustainable production system with low need of energy, water and nutrition. The name of the project is SeraCulture.

During the project the focus concerning the realisation of the Sustainable innovation greenhouse was laid on the Western part of Turkey, since:

- The focus of large investors lays on the Western part of Turkey.
- The region in the Western part of Turkey is developing fast concerning horticultural activities.
- Geothermal sources are available in the Western region.
- The climate in Western Turkey is favourable for horticultural production in greenhouses.

Designing protected cultivation systems is a multi-factorial optimization problem. During the design process, choices have to be made with respect to greenhouse construction, cladding material, climate conditioning equipment, energy sources, energy management, light management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, market, legislation and availability of resources, the degree of technology chosen. The choices made also strongly influence the economic result.

One of the most important factors influencing the optimum greenhouse design is the given outside climate of a location. It strongly influences the greenhouse inside climate and therefore crop production inside the greenhouse to a large extend. Next to that special attention was given to the availability of electric power, energy sources, water, local costs and prices, as well as to prices of equipment. The availability of capital was estimated to be no problem, since this project is focussed on large investors in the Western part of Turkey. The solution presented here therefore can be different from solutions for small scale Turkish farms in other regions of Turkey. It is assumed that enough skilled and highly educated people will be available for the operation of the Sustainable Innovation Centre. Equipment and cultivation systems were assumed to be imported to Turkey, since this is one of the goals of the 2g@there project SeraCulture, for which this study is done for. On the other hand the economic cost and benefit ratio will play a major role in the decisions made next to several indicators of sustainability. A combination of Turkish and Dutch technology is endeavoured.

The design process started with the definition of the requirements of the total system. In our case low energy input, use of sustainable energy / geothermal heat, high water use efficiency, high production and product quality and predictability of production, high food safety by low pesticide use, high ratio of benefit and costs of the production system were required. Then a system analysis revealed the functions needed, here heating, cooling, humidification and dehumidification, CO_2 application, water and nutrient supply, light management. For each function alternative working principles were worked out. For example, in case of cooling we considered natural ventilation, recirculation fans, fogging systems and shading screens as design alternatives. Similar alternative working principles have to be described during this phase for the other functions. In our study different stages of technology were analysed as different greenhouse concepts, like greenhouse with only heating and cooling by natural ventilation, greenhouse with heating and cooling by fogging, greenhouse with heating, fogging and CO_2 application etc. These different designs were then evaluated by experts (companies and scientists), model calculations and decision support systems. In our study the virtual dynamic greenhouse climate model KASPRO was used next to CFD calculations and a specific economic model. Special attention was given to expert views.

By following the steps of the design methodology at the end the optimum greenhouse design for the Sustainable Innovation Greenhouse could be chosen. The optimum system consists of a 1-2 ha Venlo-type greenhouse with continuous roof ventilation and is suitable for tomato crop production. The greenhouse will be equipped with a heating system and heat exchanger based on a geothermal well with sufficient amount of water at high temperatures. The heat from the geothermal well will first be used in the energy plant to produce electricity; the waste heat will then be used to heat greenhouses before it will be re-injected again in the ground. The use of CO_2 is of great importance for a viable greenhouse crop; ideally it could be obtained from the geothermal well. A horizontal energy screen system will be installed in order to increase energy efficiency, have better temperature distributions in winter time on half of the area. An aluminized energy cloth will be chosen with maximum energy saving on half of the greenhouse area. During summer time the aluminized energy screen will not be used. On the other half of the area a traditional combination screen will be installed, with 30% shading, which can also be used during summer time and gives less energy saving during winter time. All vents will be equipped with an anti-thrips insect netting system. A closed irrigation system will be installed in order to save water and minimize nutrient emissions. The drain from the irrigation system will be collected and stored and sterilized with heat preferable. For heat sterilization the heat from the geothermal well can be used. To enable humidity control as well as control of summer temperatures, a medium pressure fogging system will be installed. The control of excessive heat in summer will be done by this fogging system and the high ventilation capacity through the continuous roof ventilation. The greenhouse climate control will be done automatically by a greenhouse climate computer, which automatically controls heating, ventilation, fogging, CO_2 application, screen opening and water and nutrient application due to the given setpoints. Within the system the crop will be planted at the end of July or the beginning of August and ended at the end of June. Locally produced organic substrate (sustainable, no waste) will be used.

After realising the Sustainable Innovation Greenhouse next year it is highly recommended that a thorough technical, economical and sustainable analysis will be carried out based on continuous monitoring and real data collection. Special attention should be given to the different indicators of sustainability and all economic data. Other future activities should be a good knowledge transfer programme and a well thought-out communication strategy with Turkish stakeholders in order to make the project successful for the Dutch SeraCulture participating companies.

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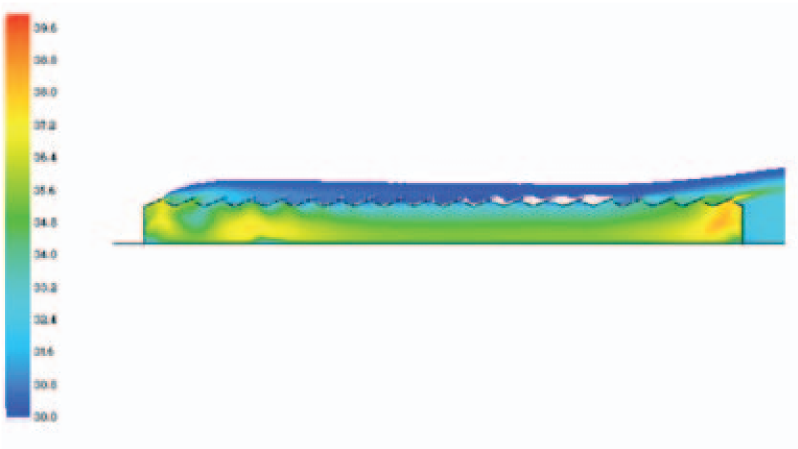
Appendix

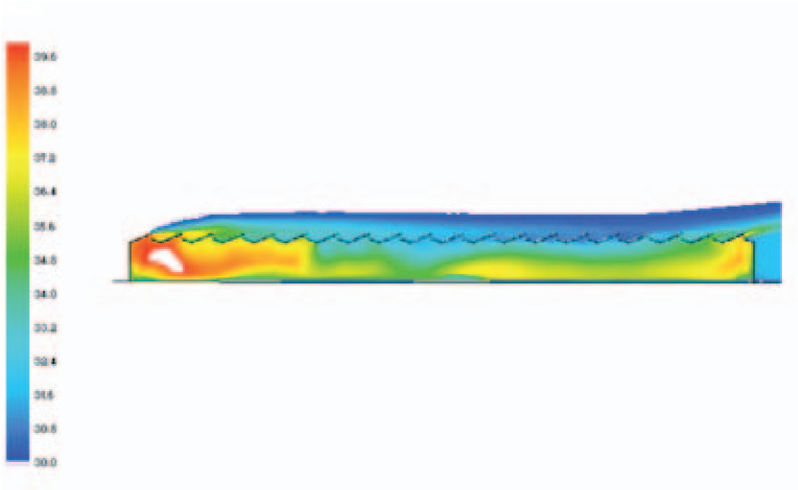
A. Definition of CFD turbulence model and boundary conditions

A.1 Definition of turbulence model

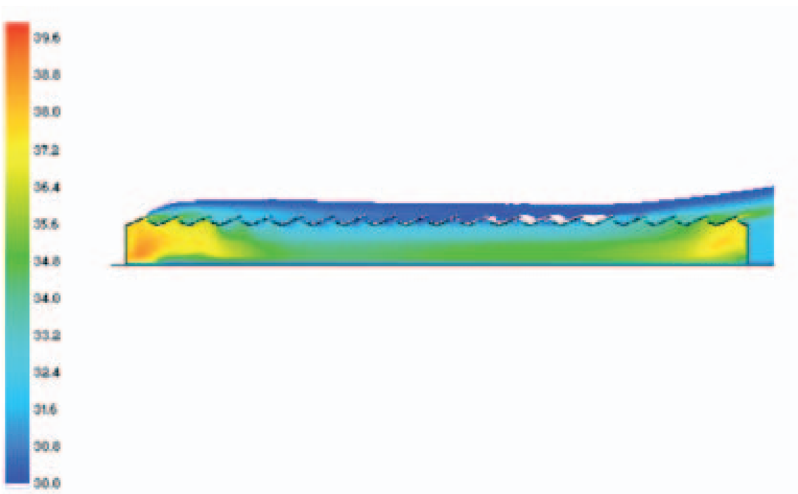
One of the most important aspects in CFD modelling is the choice of the proper turbulence model. Several studies have focused on the effect of various turbulence models on the final numerical solution, showing that no general rules could be applied in all simulation models. The most common used turbulence model is the standard k-ε which, has been tested in many cases describing the ventilation process in greenhouses. Despite it's widely usage the standard k-ε model has small accuracy especially in low velocity magnitudes and should be carefully used. In addition, it contains many empirical constants that have long been known to have an adverse effect on prediction performance (Versteeg and Malalsekeera, 1995). In recent times engineers have turned to more complex turbulence models like the two-scale k–ε turbulence models such as the renormalisation group (RNG) and the realizable k–ε, which are not so reliant on empiricism. In a two-dimensional wind induced ventilation study (Mistriotis *et al.* 1997) showed that better qualitative agreement with experimentally observed flow patterns could be achieved with a two-scale k–ε turbulence model than with the standard k–ε one. In a similar study concerning the simulation of pollutant dispersion in an urban street canyon, carried out by Sapounas and Campen (2003) four turbulence models were validated against experimental data presented by Gerdes *et al.* (1999); the standard k-ε, the RNG k-ε, the realizable k-ε and the RSM. All the models were tested for two different boundary conditions concerning the turbulence Intensity 'I' in order to find the influence of Reynolds number, I=5.8% and I=0.1% (Fluent, 1998). In this study, the results concerning the absolute percentage variations between the experimental values and computational results, provided by four turbulence models ranged from 5.6% to 118.2%. The sensitivity analysis showed that the most appropriate turbulence model was the realizable k-ε one. The same turbulence model was proposed by Garcia Sagrado *et al.* (2002) in a similar study. Although, the realizable k-ε turbulence model performs relative better according to above mentioned studies, recent ones proposed the RNG k-ε as the most accurate turbulence model, regarding natural ventilation problems, (Bartzanas *et al.* 2007, and Stavrakakis *et al.* 2008). These differences indicate firstly that indeed the standard k-ε turbulence model is not accurate enough, and secondly the necessity of performing preliminary calculations in order to determine the most appropriate turbulence model. In this direction, a 2D simulation model of 1 ha greenhouse with its surrounding was designed and tested using different turbulence models and wall functions, (Figures 10.1 & 10.2). The results shown that the best combination between physically sounds results and convergence performance was obtained by using the realizable k-ε turbulence model with no-equilibrium wall functions (Fluent, 2008).



Standard k-ε turbulence model, standard wall functions, 130 iterations, good convergence performance

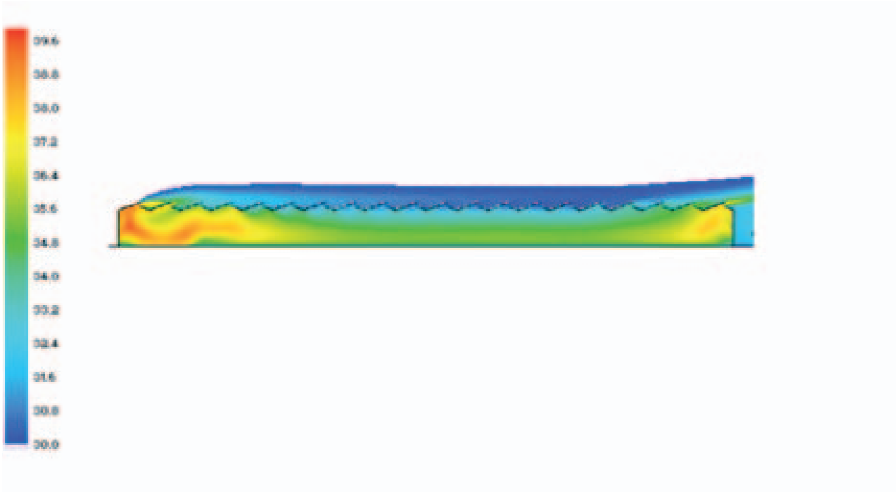


RNG k-ε turbulence model, standard wall functions, 130 iterations, very bad convergence performance

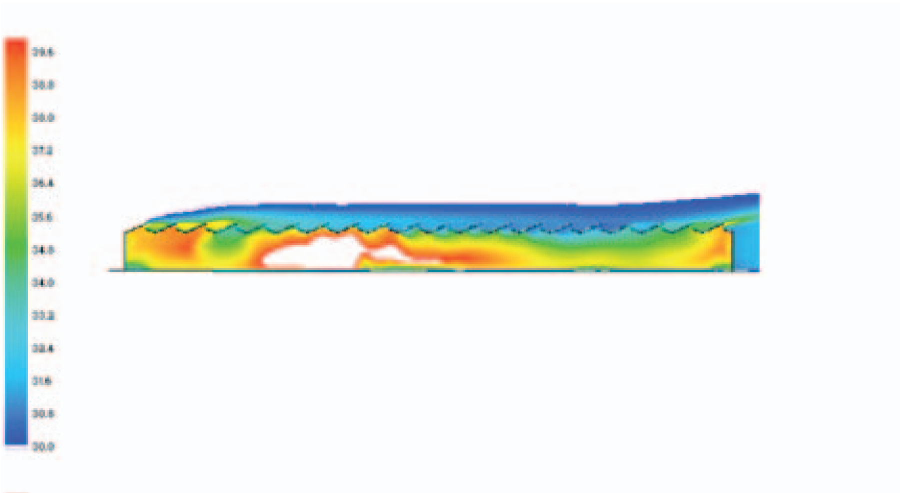


Realizable k-ε turbulence model, standard wall functions, 130 iterations, good convergence performance

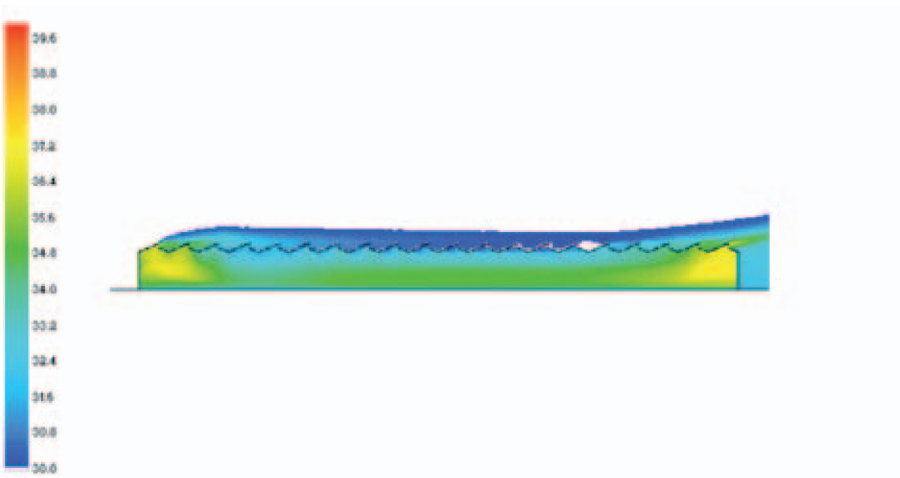
Figure 10.1 Contours of air temperature inside the greenhouse as obtained using different turbulence models with standard wall functions approach



Standard k-ε turbulence model, non equilibrium wall functions, 130 iterations, not good convergence performance



RNG k-ε turbulence model, standard wall functions, 130 iterations, very bad convergence performance



Realizable k-ε turbulence model, standard non equilibrium wall functions, 130 iterations, very good convergence performance

Figure 10.2 Contours of air temperature inside the greenhouse as obtained using different turbulence models with non equilibrium wall functions approach

A.2 Definition of boundary conditions

For the inlet boundary condition a wind profile which is produced according the 'Log wind Profile' was used. The Log wind profile is a semi-empirical relationship used to describe the vertical distribution of horizontal wind speeds above the ground within the atmospheric surface layer. The logarithmic profile of wind speeds is generally limited to the lowest 100 meters of the atmosphere (i.e. the surface layer of the atmospheric boundary layer). The wind speed u_z at height z (m) above the ground is given by the Eq. (2):

$$u_z = \frac{u_*}{k}\ln\left(\frac{z-d}{z_0}\right) + \varphi\left(z, z_0, L\right) \tag{2}$$

Where:

u_z is the velocity at height z (m s^{-1})

u_* is the friction or shear velocity (m s^{-1}) which is given by the Eq. (3)

$$u_* = u_z \frac{k}{\ln\left(z/z_0\right)} \tag{3}$$

k is the von Karman's constant (~0.41)

d is the zero plane displacement (m)

z_0 is the surface roughness (m)

L is the Monin-Obukhov stability parameter. Under neutral stability, $z/L = 0$ and φ drops out.

Zero-plane displacement d is the height in meters above the ground at which zero wind speed is achieved as a result of flow obstacles such as trees or buildings. It is generally approximated as 2/3 of the average height of the obstacles. For example, if estimating winds over a forest canopy of height h = 30 m, the zero-plane displacement would be d = 20 m. Roughness length (z_0) is a corrective measure to account for the effect of the roughness of a surface on wind flow, and is between 1/10 and 1/30 of the average height of the roughness elements on the ground. Over smooth, open water, expect a value around 0.0002 m, while over flat, open grassland $z_0 \approx 0.03$ m, cropland ≈ 0.1-0.25 m, and brush or forest ≈ 0.5-1.0 m (values above 1 m are rare and indicate excessively rough terrain). The log wind profile is generally considered to be a more reliable estimator than the Wind profile power law, which is commonly used when neutral conditions are assumed and roughness information is not available.

In order to define the boundary conditions for the recirculation fans a pre-model was developed to investigate the influence of the turbulence characteristics to the numerical solution. The model was solved taking into account the operational characteristics of the fans (TB4E40Q and TB4E50Q) by performing a sensitivity analysis regarding the influence of turbulence intensity to velocity magnitude (Figure 10.3).

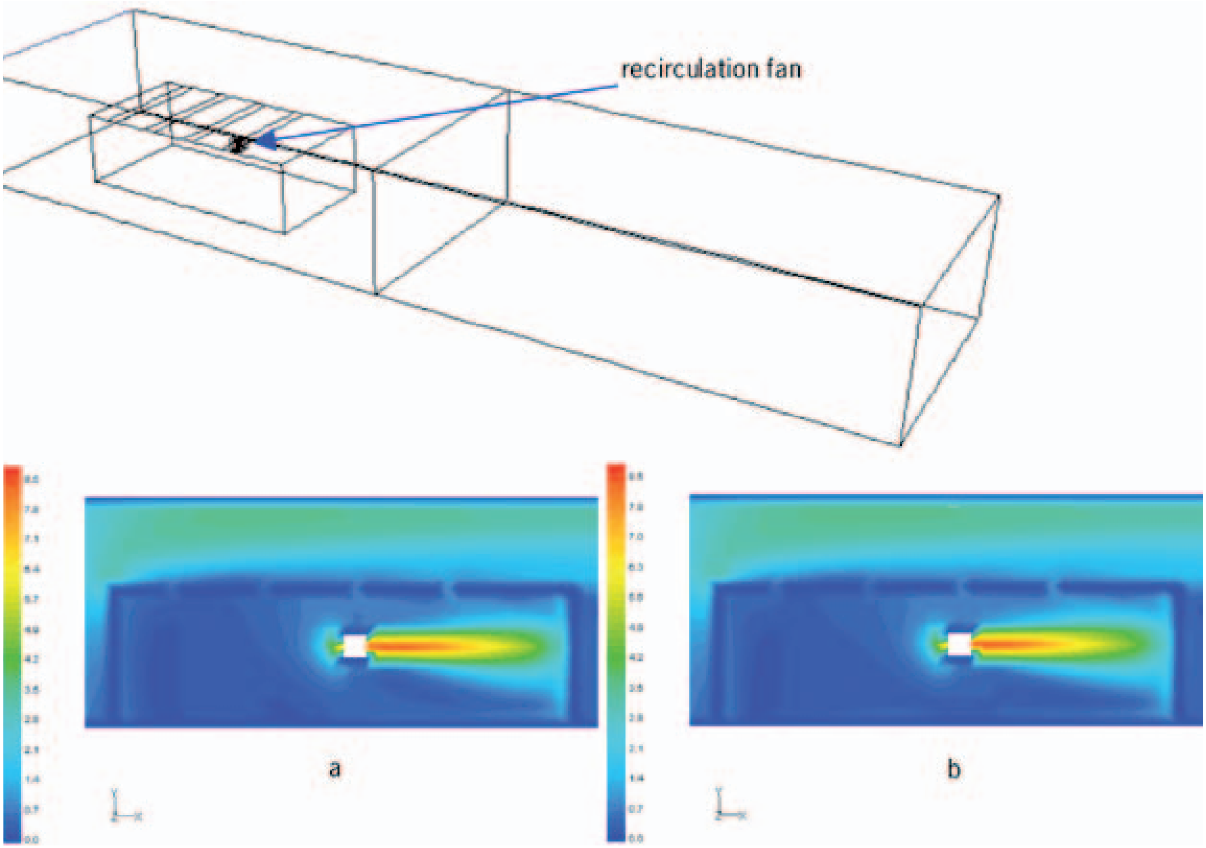


Figure 10.3 Contours of velocity magnitude inside a test-cell ventilated by recirculation fan roof openings, (a) turbulence intensity = 5% and turbulence length scale = 0.0035 and (b) turbulence intensity = 2% and turbulence length scale = 0.0035

SeraCulture

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Agentschap NL
Ministerie van Economische Zaken

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