The Solar Greenhouse: a Highly Insulated Greenhouse Design with an Inflated Roof System with PVDF or ETFE Membranes

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Abstract

In a co-operation project of Wageningen University (Wageningen UR), Agrotechnology & Food Innovations B.V. (A&F), Priva Hortimation B.V. and Hyplast N.V. (Belgium) a greenhouse for the future has been developed. The project has four lines, namely 1. lowering the energy demand, 2. using solar energy for heating (greenhouse as solar collector), 3. modifying climate control and dehumidification and 4. developing of the highly insulated greenhouse. This paper deals with the development of the so-called Solar Greenhouse, the structure and cladding material and the (natural) ventilation openings.

The aspects that play an important role in the process of development of the greenhouse are the strength of the structure, the light transmittance, the material consumption and the expected greenhouse climate. The high demands for energy savings lead to a greenhouse covering with a high insulation value and at the same time a high light transmittance. Advanced materials like fluor polymer films in double or more layers with the space in between inflated have these qualities.

The most perspective greenhouse geometry is a saw-tooth roof structure with roof inclinations of 20^0 and 30^0, a span width of 10m and a vertical opening of 2 m for natural ventilation. The module for the greenhouse is repeatable in both directions to a big area. Caused by the asymmetric geometry of the greenhouse (openings oriented on one side) the influence of the wind and wind direction is extensive.

INTRODUCTION

The Solar Greenhouse project aimed at the development of a greenhouse system for high value crop production with sustainable energy supply. The project meets the Dutch governmental goal to substantially decrease energy consumption and increase the contribution of sustainable energy (Glami, 1990). Moreover CO_2 emission must be reduced considerably. Greenhouse horticulture uses 12.5% of the total natural gas production in The Netherlands. This means also an emission of more than 7.2 million tons of CO_2 per year. Reduction of fossil energy and replacing this by sustainable energy (solar and wind energy) has the highest priority. The emissions in greenhouse horticulture to soil, water and air must be strongly reduced. This has also an economic target, because the energy costs are now about 25% of the total production costs in The Netherlands.

Around 1997, when the solar greenhouse project started, the energy consumption per unit produce (EPE) was about 60%. In 2000 the level was 56%. In a new agreement between industry and government it was fixed that the EPE must be reduced in 2010 to 35%. This means a reduction of almost 40% compared to the year 2000.

Simple measures like installing a moveable energy screen in traditional greenhouses or by improving the existing designs on a small scale are not enough. New advanced structures applied with materials of the future have to be considered to fulfill the demands for energy saving and high light transmission.

MATERIALS AND METHODS

In a previous study several designs were developed, which could be interesting for this purpose (Waaijenberg and Hoffmann, 2001). Here an inventory is carried out based on traditional greenhouse structures and advanced systems used in civil engineering, like membrane and pneumatic structures. The five most promising designs were chosen and worked out for this project.

The Greenhouse Design

To be able to see the effects of light interception by structural parts and transmission through the cladding material a computer model has been developed based on ray tracing (Swinkels, 1999). Also a database with measured results of greenhouse cladding materials and screens is set up and used to select suitable materials.

From the five most promising greenhouse designs the one with the highest light transmission and very good insulation is chosen. This is a greenhouse design with saw-tooth roof shape and ventilation openings in the roof area (see Fig. 1).

The type of construction described here with cables and flexible claddings have a high light transmission due to the advanced covering material but also due to less construction elements. Caused by using a double inflated roof structure the insulation value of this greenhouse is much better then that of a conventional greenhouse with single cladding. Traditional steel trusses are used in combination with tensioned structural cables (Twaron®) and plastic high-tech membranes. The span width is 10 m, the gutter height 4 m and the roofs have a saw-tooth shape with optimum roof inclinations of 20^0 and 30^0. The greenhouse has a natural ventilation system with vertical openings in the roof (height of 2 m). Inflating plastic tubes close the ventilation opening and by deflating this tubes again it opens (see Fig. 1). The investigated properties of this design are the strength, the light transmittance, the expected indoor climate and the material consume.

After many optimization steps the geometry of the greenhouse, the dimensions of the steel profiles and cables in combination with tensioned membranes are specified (see 2.1.2).

1. Plastic Membrane Covering. The cladding material for this greenhouse design must have a high light transmittance and must be applied as a double layer structure to realize the necessary energy saving. The easiest way to come to a double structure with a high light transmittance is to inflate the space in between the films and to keep a constant overpressure by using a small fan. The research for developing the greenhouse cladding material focused on advanced plastic membranes, because with this material the highest light transmittance can be reached. At first the polymer TPU (thermoplastic polyurethane) was investigated, because this material has a high durability (about ten years) and light transmittance (92% for direct light). The disadvantages of this material however could not be solved, namely the high creep at high temperatures and the low modulus of elasticity (E-modulus). The next material was PVDF co-polymer (polyvinylidene difluoride), which has a comparable durability and light transmittance (93% for direct light) as TPU, but has better mechanical properties. A test membrane was produced as a co-extrusion film at a thickness of 145 µm. The original disadvantage of this material was the weak tear resistance, which appeared to be critical in greenhouse application (Waaijenberg and Frénay, 1993). This property was strongly improved in the test membrane. The smoothness of PVDF asks for special facilities to fix the membrane properly to the structure (clamping profiles). Therefore a special research is executed regarding fixing systems for this type of membrane materials (Doremaele, van, 1998). The material ETFE (ethylene tetra fluoroethylene) has almost the same good properties as PVDF (ETFE has a somewhat higher transmittance for direct light then PVDF, namely 94%) and is available now as a commercial membrane in practice (also with anti-condensation properties).

Tests are also done to improve the properties of standard LDPE films (low density polyethylene) (Waaijenberg and Verlodt, 2000). For example to decrease the radiation losses in the thermal infrared area it is possible to lower the emission coefficient. Adding coatings to the film or adding metal oxides (additives) to the raw material can realize this.

2. Strength Calculations. A greenhouse structure has to carry all loads, like permanent (self weight), installations, service loads and suspended crops and must withstand the outdoor weather stresses such as wind, snow, rain and hail. To avoid damage the structure has to be calculated according national standards. The Dutch standard is NEN 3859 (NEN 3859, 1996) together with a special Practice Guideline written for greenhouses with flexible claddings (Braam et al., 1997). Since the European standard EN 13031-1 (EN 13031-1, 2002) is still rather new, the Dutch standard NEN 3859 is followed for the calculations of the solar greenhouse.

Special calculation software was used for the design process and to check the structural strength and safety (see Fig. 2). This software, which originates from the USA, is able to handle three-dimensional (3D) structures and is also able to consider flexible membranes and tensioned cables (Hemming et al., 2002).

The following load combinations were considered:

- Permanent load + snow load + permanently present installation load;
- Permanent load + wind load;
- Permanent load + crop load + permanently present installation load + service load;
- Permanent load + crop load + permanently present installation load + wind load.

The results of the analysis of the different loads and load combinations are the forces and moments acting on the different structural elements, like beams, cables and membranes. These forces and moments result in material stresses that make it possible to check if all elements are strong enough (compared to the maximum allowable stress).

It appeared that the stretched plastic membranes (double membrane inflated) have a major contribution to the structural strength of the design. Prestresses in the membrane and overpressure between the inflated plastic layers reinforce the construction. The membrane is able to carry external loads and transmit them via beams and structural cables to the ground. Since cables can only handle tension forces the beams must handle the bending moments. The module of the solar greenhouse has dimensions of 10 x 10 m. Several spans next to each other contribute to the stability of the neighboring span. That is the reason why the profiles for the multi-span greenhouse are lighter then those of the single-span. Standard profiles were used for this prototype calculation. In a follow-up of this project these profiles can be optimized. The material properties and dimensions of the structural elements, which are necessary to withstand all load combinations, are given in Table 1.

Although the dimensions of the profiles look quit big, the material consume for the structure of the solar greenhouse is only 2.5 kg/m^2. This must be compared to the weight of a standard Venlo-type greenhouse covered with single glass, which is 5.5 kg/m^2 for the structure only. When looking at the weight of the total greenhouse, including the cladding material, the material consume of the solar greenhouse is 2.7 kg/m^2 compared to 19.5 kg/m^2 for the traditional glass greenhouse.

3. Climate Simulations. Besides heating installations, outdoor weather conditions etc. natural ventilation, covering material, construction materials and the whole design are the factors influencing the greenhouse climate. This solar greenhouse is not designed as a completely closed greenhouse where the indoor climate is ruled by artificial installations for cooling etc., but it is applied with equipment for natural ventilation, because of the huge heat load during summer (also in The Netherlands !) and the big quantity of energy needed to cool the greenhouse in summer. The closable ventilation opening is located in the vertical part near the ridge of the greenhouse. Natural ventilation is driven by pressure differences created either by wind or by temperature differences. The air-flow caused by temperature differences is called the ‘buoyancy effect’ (Papadakis et al., 1996). If the wind speed is lower then 0.5 m/s, the buoyancy effect is very important, while when the wind speed is greater then 1.8 m/s the natural ventilation is mostly driven by wind. For the intermediate case both mechanisms have influence. The situation of high outdoor temperatures and no wind is most critical for sufficient greenhouse climate.

In the past experimental investigations about the greenhouse climate were done by tracer-gas experiments or by measurements in full-scale greenhouses. Nowadays it is possible to simulate practical situations regarding the greenhouse climate due to powerful computers and computational fluid dynamics (CFD) software. This makes it possible to calculate designs without the need to build a prototype. CFD becomes a widely used tool to determine flow field and temperature distributions in and around geometries. A general description of CFD is given by Mistriotis (1997). Because the critical situation is during hot days without wind the outdoor temperature is set to 25^{0}C, the sensible heat production to 450 W/m^2 and the outdoor radiation to 900 W/m^2 (about 50% of the incoming radiation is assumed to be transferred to sensible heat and 50% to latent heat used for transpiration and evaporation mainly). The crop height is set to 3 m. The heat transfer coefficient is set to 5 W/m^{2}K for the heat transfer from the cladding material to outside.

The output of the simulations are: the ventilation rate, the maximum temperatures and the temperature distribution figure. High temperatures can be accepted if they do not appear in the crop layer (from 0 to 3 m height). The ventilation rate is given in renewals per hour (1/h) defined by the total volume of air leaving the model during one hour and divided by the total volume of the model. The parameters that are variable during the simulation process are: the geometry of the greenhouse (different height, roof inclinations, dimensions of the ventilation opening), average wind speed in relation of the location of the ventilation openings and the wind direction, closing and opening of the ventilation windows and built as a single-span or multi-span greenhouse. All variations of the parameters of the solar greenhouse design are compared to similar conditions for a standard Venlo-type greenhouse with single glass covering.

The simulations show that a ventilation rate of maximum 25 1/h can be reached in the situation without wind in a multi-span and 53 1/h at a wind speed of 6 m/s. Unfortunately the maximum temperature is still high with temperatures above 40^{0}C at some locations in the greenhouse in the situation without wind. With wind these high temperatures only occur in the boundary areas next to the sidewalls. In the other parts of the greenhouse the horizontal temperature gradient is very small (about 2-4^{0}C). The vertical temperature gradient is comparable to the Venlo greenhouse with 5^{0}C.

4. Light Transmission. Light is an essential factor for plant growth. Photosynthesis and photomorphogenesis are the two most important processes affected by light. So a cladding material should always have a maximum light transmittance. However to reach the governmental goal for energy saving in greenhouses it appeared to be necessary to get materials or combinations of cladding materials, which have a much better insulation value then the traditional material single glass or single plastic PE-film. Therefore double layered acrylic and polycarbonate sheets were applied as greenhouse cladding materials in the past. Unfortunately these double sheets create a light loss of about 10% compared to single glass. New materials like PVDF and ETFE-membranes now give the possibility to make a double inflated structure, which has a light transmittance comparable to single glass thanks to the very high initial light transmittance of this fluor films. Other materials have perfect thermal properties but a low light transmittance or they do not have the right mechanical properties (see under 2.1.1).

The dimensions of all structural elements are used as input for the computer program TRANSKAS to calculate the expected light transmittance of the greenhouse. This is a program developed by A&F in Wageningen, which also takes in account the interception of light by the cladding material, by solid profiles and cables and the reflection of light by the sides of the profiles (Kieboom and Stoffers, 1985). As output the program gives the transmittance for diffuse light in the greenhouse at plant level in the wavelength of 400-700 nm (PAR). During the calculations with this program the roof angle, the geometry of the greenhouse and the number of layers of the covering material were varied to be able to find the optimum solar greenhouse design based on the light transmittance for diffuse light. In countries like The Netherlands the transmittance for diffuse light is the most important parameter, because during winter season 75% of the natural light is diffuse due to clouds.

The optimum design for the solar greenhouse has roof inclinations of 20^0 and 30^0 and a continuous ventilation opening with a height of 2 m, location vertical plane 6 m from the gutter measured horizontally (see Fig. 2). The transmittance for diffuse light of this solar greenhouse design is 78%. This is better than the transmittance of a single glass-covered Venlo-type greenhouse with spans of 4 m, which diffuse transmittance is 75%. It has to be considered that the value for the solar greenhouse is valid for a double layer covering, while the value for the Venlo-type greenhouse is only for a single glass covering.

CONCLUSIONS

The new solar greenhouse design includes a structure with steel columns and trusses and tensioned aramide (Twaron®) cables. It is designed with a two layer covering of PVDF or ETFE membranes. It has a high light transmittance (maximum 78% for diffuse light) and is capable to carry all loads specified in the Dutch standard NEN 3859. Because air is pumped between the plastic membranes (inflated roof), the air layer acts as an insulation layer. The energy consumption of the greenhouse is minimized. Also the air layer under pressure gives a contribution to the stability of the greenhouse system regarding wind and snow loads. The roof has a saw-tooth shape; the side of the roof facing south has a higher inclination than the roof facing north. Light transmittance calculations show an optimal roof inclination of 20^0 and 30^0.

Since the roof ventilation openings are located on one side of the ridge the ventilation effectivity is dependent on the wind direction. To improve this orientation limitations the repeating roofs could be built in turns: one roof opening is facing north and the next one facing south.

All dimensions of the structural elements were determined by following the Dutch standard NEN 3859. The elements are optimized for a multi-span greenhouse. The geometry of the profiles can be optimized more in future (by using other then standard profiles).

The ventilation rate of the multi-span model of the solar greenhouse is estimated to about 25 1/h and the maximum temperature inside the greenhouse is locally 42^0 in case of no wind.

The horizontal temperature gradient is very small (2-4^0C) and the vertical gradient is comparable to that of a Venlo-type greenhouse (5%). The regions with high temperatures in the greenhouse can be avoided by cutting off half of a span (starting with a vertical sidewall underneath the first ridge) or integrating side-wall openings on both sides of the design (see Fig. 3).

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Tables

Table 1. Material properties and dimensions of the structural elements used for the single and the multi-span solar greenhouse.

Properties	**Single-span**	**Multi-span**
Column (mm)	120x120x6.3	100x100x2.6
Ground horizontal (mm)	120x120x6.3	None
Gutter horizontal (mm)	120x120x6.3	100x100x2.6
Cables	Twaron 9.5 mm	Twaron 9.5 mm
Membranes	ETFE 100 µm	ETFE 100 µm
Prestress cables in roof (kN)	60-100	60-100
Prestress guy-cables (kN)	8-80	10-80
Prestress membrane (kN)	2.63x2.63	2.63x2.63

Figures

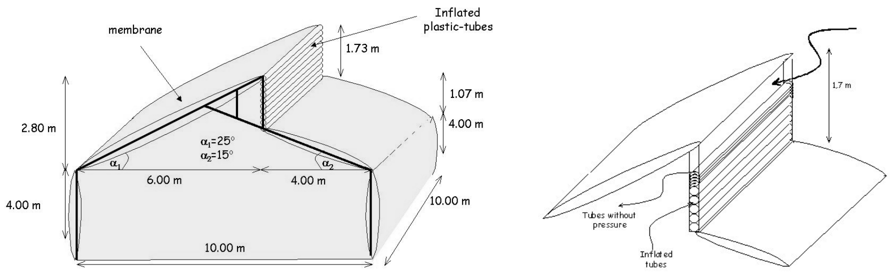

Fig. 1. Drawing of the design for the solar greenhouse with the double cladding (inflated) with the chosen dimensions and the principle of opening and closing the natural ventilation system.

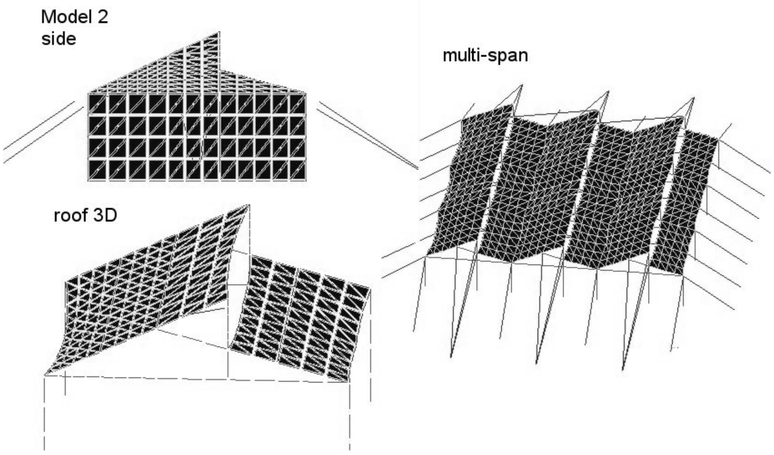

Fig. 2. Different views of single-span and multi-span of the solar greenhouse design giving the modeling for the strength calculations.

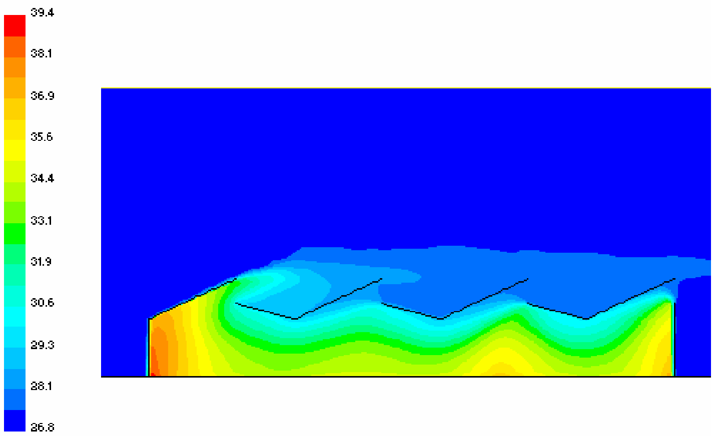

Fig. 3. Temperature distribution in the solar greenhouse with a sidewall underneath the first ridge.