Chinese – Dutch cooperation on the Chinese Solar Greenhouse experiment in Shouguang

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Abstract
The Chinese Solar Greenhouse is simple but has a low productivity. To improve this, the inner greenhouse climate will have to become more controllable. To contribute to this, but keeping the passive character of the greenhouse, meaning that it doesn’t need additional heating, the Chinese Academy of Agricultural Science has developed the Active Heat Storage and Release System (AHSRS). By switching on and off a pump that runs water along large panels along the north wall the gathering of heat and the release of heat can be controlled. This project shows that the AHSRS does not affect the diurnal average temperature in winter, but can elevate the minimum temperature by some 2 °C. On dull days, however, the AHSRS doesn’t give an improvement since it doesn’t add anything to the shortage of energy.

The fact that the Chinese Solar Greenhouse prevents frost, despite outside temperatures that may go down far below -10 °C is largely due to the high insulation applied. The insulation can be further increased by using screens inside the greenhouse. This project shows that such a screen may elevate the temperatures on the coldest days with about 1.5 °C and in Chinese Solar Greenhouse with the AHSRS even slightly more.

When using a transparent screen like the Ludvig Svensson Luxous screen, the elevated temperature in winter comes together with a slightly increased amount of light entering the greenhouse. In warmer months of the year, the light entrance to the greenhouse will be reduced somewhat when using a thermal screen.

Apart from temperature, also the humidity is often unfavourably high in the Chinese Solar Greenhouse. This report shows a simple system to reduce the high humidities in winter at the expense of about 7 kWh/m² of electricity per year.

Another topic studied in this project was the use of soilless cultivation. The equipment, consisting of a irrigation and nutrient supply system, drippers and coco fiber slabs, worked well and contributed to a good an healthy crop. To achieve this, the greenhouse operator was helped a lot by the Delphy advisory service.

The control of all actuators and measurement of the greenhouse and outside climate was carried out by the Hoogendoorn ISII greenhouse climate computer. After a short period the operator of the greenhouse learned how to use the outputs of the climate computer and its control capabilities to realize the best possible climate with the given, limited number of control possibilities of a Chines Solar Greenhouse.

The harvest in terms of tomatoes in this first experimental period was about 5.5 kg/m². This is still very low, but largely due to the start-up character of this first year. It is stated that a production of 20 kg/m² is reasonable to expect, providing a good support by a knowledgeable adviser.

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Preface

With the fast growth of Chinese cities and the general growth of wealth, the Chinese market for fresh vegetables like tomato, cucumber, sweet pepper and egg plant is growing. These vegetables are ideally grown in greenhouses to ensure a high quality. China has a lot of experience with greenhouses but these greenhouses are typically small and have a low productivity. Research, demonstration and extension on improved greenhouses and growing techniques are therefore needed. The joint effort of Chinese universities and Dutch companies representing the leading techniques will speed up this development and will result in a productive and sustainable production system for vegetables.
The Chinese Solar Greenhouse is normally a passive greenhouse, meaning that it is only heated by the sun. Due to a solar heat capturing south wall, a heavy insulation and a relatively small growing area, the inner temperature can be kept more than 20 °C above the (freezing) outside temperatures, providing sunny days. The insulation comes from thick north, east and west walls and an insulating blanket at the outside of the greenhouse. This blanket can be rolled down in the late afternoon and stowed on top of the greenhouse in the morning.

The cropping area ranges between 150 to 900 m² and is typically 1 Mu, which is 400 m². The crop is typically grown in the soil and watering is traditionally performed manually through a network of small ditches.

The challenges faced with the Chinese Solar Greenhouse is the inhomogeneity of the temperature in the greenhouse, the very high humidity during the night, the high temperatures in summer and the sometimes much to low temperatures in winter. Also the small size of the greenhouses is a difficulty since it hampers to make advantage of economies of scale. The Chinese Academy of Agricultural Sciences (CAAS) is working on addressing these challenges, together with the Shouguang Vegetable Group.

The first tool to improve the performance of the Chinese Solar greenhouse is to improve the temperature regime. Traditionally, the temperature just comes as a result of solar radiation and thermal energy dynamics of the thick northern wall. This wall heats up by interception of direct solar radiation during the day and releases heat when the greenhouse temperature becomes lower than the wall temperature. In a new design of CAAS, the passive process of gathering and releasing heat is replaced by an active system using water to transport and store energy. This system is called the Active Heat Storage and Release System (AHSRS). By switching on and off a pump that runs water along large panels along the inside of the north wall the gathering of heat and the release of heat can be controlled.

During the experiment, which started not earlier than February 3rd of 2015, there were only 6 days where the AHSRS was actually working, meaning that there was a charging during the day and discharge during the night. It could be concluded that the AHSRS can gather and release about 0.6 MJ per m² greenhouse per day. The measurements also show that it is advisable to stop running the pump earlier in the afternoon because almost every day it could be seen that accumulated heat already started to be released before the pump was switched off.

The small number of days gave no possibility to say something of the effect of the AHSRS on the greenhouse temperature. Moreover, the experiment did not include data for comparison with a standard Chinese Solar Greenhouse. Therefore, a simulation model was used to compute the expected result of the AHSRS. The model was developed as an additional module to the Wageningen UR greenhouse simulation model KASPRO. The structure and parameters of this model extension are presented and explained and results of the model are compared with measurements from the Shouguang experiments. It was concluded that the model performs reasonably well and therefore the model was used to observe the expected effect of the ASHRS in a normal growing season, which starts in September and runs till May.

The simulations show that in autumn and spring the greenhouse with an AHSRS like the one used in the current experiment will be about 2 degrees colder than the reference greenhouse, but that in the winter months the AHSRS greenhouse will be slightly warmer (about 0.3 to 1 °C).

The lower temperatures in autumn and spring are a result of the smaller heat capacity of the greenhouse with AHSRS. This makes that the greenhouse warms more quickly during the day, which results in an earlier opening of the ventilation openings and, with that, a loss of energy.

In winter, the average temperature of the greenhouse with AHSRS is higher because of the reduced heat losses through the walls. So, in fact, this is not caused by the active character of the system, but mainly because of the application of modern insulation materials instead of the traditional thick earth wall. Where the average temperatures in winter for a greenhouse with AHSRS hardly differ, the minimum temperatures can be elevated by about 2 °C during most nights in winter. Only on dull days (days with less than 5 MJ of solar radiation per m²), again, the Chinese Solar Greenhouse with AHSRS did not differ from the standard Chinese Solar Greenhouse. This is because on dull days there is hardly any heat accumulated in the storage system, so there is nothing to control either.
The fact that the Chinese Solar Greenhouse prevents frost, despite outside temperatures that may go down far below -10 °C is largely due to the use of the outside insulating blanket. The important disadvantage of this blanket, however, is the fact that a deployed blanket blocks all light entrance. Both for crop growth as for heat accumulation, the blanket has to be stowed, but it needs quite some time after sunrise in the morning before the blanket can be rolled up without causing a temperature drop too large. Therefore, the solar light in the first and last hours of the day cannot be used for plant growth on most of the winter days.

A better insulation can be achieved by adding an additional screen inside the greenhouse. Because of the protective covering by the greenhouse envelope, such a screen can be made from thin and light materials. This enables an automated opening and closing system.

In the experiment, half of the greenhouses are equipped with an automated moveable screen. However, also for this component, the final realisation of the system took that long that no useable data on the effect of the screen on temperatures in the greenhouse could be measured. By the time that the mechanism and its control was finished, the outside temperatures have become that high that the screen was not used anymore. Therefore, also for the thermal screen the performance was determined by simulation. The model computations show an increment of the daily average temperature of 1.5 °C for the coldest days for a standard Chinese Solar Greenhouse. For the Solar Greenhouse with the AHSRS, the increment of temperature on the coldest days was even slightly more.

The major advantage of a thermal screen as used in the Shouguang experiment (Ludvig Svensson Luxous screen) however is its transparency. As the screen provides additional insulation when deployed, the period with a deployed outside blanket could be shortened when using such an inside thermal screen. Then, on a daily base, more light may enter the greenhouse without resulting in temperatures too low.

To evaluate the possibilities, the simulation model was used to make computations on the effect of shortening the deployment of the outside blanket while (partly) compensating for the reduced insulation by the transparent inside thermal screen.

The model computations show that with such a thermal screen the outside blanket can be stowed two hours more per day, without a reduction of greenhouse temperature. This allows for more light in the greenhouse. However, the additional amount of light is very limited. The model computes an increment of 1% in total light transmittance in December and January and a 0.5% increment in November and February. For the whole growing season, the thermal screen is computed to give a 2.5% reduction of light entrance. The limited additional light in winter, and on a yearly base even reduced amount of light is caused by the fact that the difference in deployment of the outside blanket takes place at the boundaries of the day period. This is, of course, the period that contribute only a little to the daily amount of light. Moreover, the thermal screen does intercept light when it is deployed, but also when it is stowed.

The package of the stowed screen could have been smaller when the fixing of the screen to the pulling wires would have been realized by sliding clamps instead of the rigid clamps used in the current mounting.

Apart from low temperatures, high humidities are a problem in the Chinese Solar Greenhouse as well. In this report it is explained that there are two systems to reduce humidity. The cheapest one is to exchange air between inside and outside the greenhouse. This method is limited to regions where the outside absolute humidity is predominantly lower than the humidity inside the greenhouse and may require some heating. The second possibility is to use a heat pump that creates a cold surface inside the greenhouse where moisture will condensate. Such a system works well and can be considered as an energy efficient system, although of course not as energy saving system as a passive greenhouse does not use energy at all. However, with an investment of around 75 RMB per m² greenhouse, this system was considered not to be applicable for the Chinese Solar Greenhouse.

Therefore the current report concentrates on the first system, blowing heated outside air into the greenhouse. The report presents a design of such a system that showed to work, although again, no experimental measurements on the impact on greenhouse climate can be shown. Although small (maximal 14 W/m²), the electric power needed for heating was not available. However, model computations give rise to high expectations of this dehumidification system at the expense of about 7 kWh/m² per year.
Another topic studied in this project was the use of soilless cultivation. The equipment, consisting of a irrigation and nutrient supply system, drippers and coco fiber slabs, has shown to work well and a good and healthy crop has been grown. The experience with the current drippers showed out that in future better quality drippers will have to be selected to avoid the frequent clogging that was observed. Another recommendation that followed from the experiments is that when using a drip irrigation system some back-up system for water supply has to be available to overcome periods with a power cut.

The experimental facility made use of a top of the market greenhouse climate computer. Such computers are capable of controlling heating, ventilation, illumination, screening and watering on greenhouses going up to 20 hectares or more. In a Chinese Solar Greenhouse, such computer can control only the watering and in the greenhouse with AHSRS, thermal screens and the dehumidifier it can control the switches of these devices (on/off, open/close). Also the registration of the greenhouse climate and other growing conditions can be performed by such a greenhouse climate computer, but since heating and ventilation are hardly controlled in a Chinese Solar Greenhouse, the grower can hardly apply this information for an improved crop management. Nevertheless, the experience with the Hoogendoorn ISII computer, used predominantly to control the AHSRS and the watering of the crop, showed that the operator of the greenhouse learned to manage the output of the climate computer within a day and mastered the user interface within a couple of days.

The harvest in terms of tomatoes in this first experimental period was about 5.5 kg/m². This is quite low and largely caused by the very late planting date and the very difficult start of the crop. There were no crop support wires for the first 7 weeks and after the crop was hung and reached the wire, there was no way to lower the crop. Giving these difficult conditions and the very short growing period the 5.5 kg/m² will be far from the potential production. When having enough electric power for the dehumidification system and without the problems with power cuts and lowering of the plants, a production of 20 kg/m² is reasonable to expect. To achieve such a high production, regular visits of the Delphy crop adviser, e.g. every two weeks, will be very supportive to improve the skills in using the modern equipment by the greenhouse personnel.
Introduction

China is facing a large development in the demand for fresh food and vegetables. In order to meet these demands a well-equipped greenhouse sector and educated growers will be required. Besides, such a developing greenhouse industry will promote the economic potential of the rural areas around the urban centres. The ministry of Agriculture of the People's Republic of China and the Ministry of Economic Affairs of the Kingdom of Netherlands have expressed interest to develop joint activities to improve the vegetable production and supply chain in China.

In line with the bilateral interest, Shandong Province, Shouguang Municipality, Shouguang Vegetable Industry Group, and Greenport Holland International (GHI), Wageningen UR and Delphy (formerly known as GreenQ) have signed the Sino Dutch Memorandum of Understanding on the Development of the Vegetable Sector in Shandong Province on 27th September 2012.

The Chinese Academy of Agricultural Sciences (CAAS) is also committed to contribute to this development and initiated a research contribution to the Experimental Station on Protected Agriculture which is being established in Shouguang. This experimental station is deployed in a cooperation of the Shouguang Municipality and the Shouguang Vegetable Group and finally will comprise 50 mu (3.3 hectare) site for research on vegetable production. Such a centre fits well in Shouguang, being the capital city of the Shandong province and the centre of current horticultural production in the area.

In this experimental station, various types of greenhouses are or will be built. A number of the typical Chinese Solar Greenhouse and a large number of tunnel greenhouses have been erected and multi-span greenhouses and a plant factory will be added. Correlated training facilities and laboratory facility will also be built. The actual establishment was started in 2014 and will be finished in 2016.

The different types of greenhouses of the experimental station are meant to serve different categories of entrepreneurs. Consequently, the Chinese Solar greenhouse, which is a widely used type of greenhouse, takes a prominent place in the experimental station.

This Chinese Solar Greenhouse is typically an unheated envelope with a transparent south facing covering and an insulating wall at the north, east, and west sides. The walls provide insulation and also provide a large thermal mass that attenuates the diurnal temperature fluctuations. The heat absorbed from the sun during the day by the thick wall will be released when the greenhouse cools down during the night and prevents the greenhouse to become too cold.

Chapter 1 describes the general characteristics of the Chinese Solar Greenhouse.

The process of gathering and release of solar energy from the north wall is a passive process. This makes the greenhouse simple, but controllability of the energy harvest and release from at the north wall could give the greenhouse a more favourable inner temperature regime and hence a better cropping result. To contribute to this controllability, the Chinese Academy of Agricultural Science (CAAS) has proposed to use an Active Heat Storage and Release System. This system is composed from low cost solar panels mounted at the north wall and a water tank that acts as a heat storage medium. During daytime the panels harvest solar energy and store the heat by warming the water in the tank. During night time, this warmed water is circulated over the same panels to release the energy to the greenhouse air. By on/off switching of the pump that circulates the water, both the harvest and the release can be realised on demand.

Two out of eight Chinese Solar Greenhouses of the experimental station are equipped with such an Active Heat Storage and Release System (AHSRS) in order to be able to investigate the benefits of the controllability of the solar energy application. Unfortunately, there are only very limited measurements on the performance of the AHSRS because the finishing of the greenhouses had taken much more time than anticipated. Therefore, the presentation of the perspectives of the AHSRS in the Chinese Solar Greenhouse, discussed chapter 2, is mostly based on simulations with a numerical model.

Besides a more controlled way of the application of solar energy, like aimed with the AHSRS, an increased insulation of the greenhouse will help to improve the temperature regime. Therefore, the application of a transparent thermal screen is another point of research in the experimental station. To observe the effect of such a screen, one of the Solar Greenhouses is equipped with a moveable screen. However, the mounting and control of this screen has been established well after the cold season so no effect could be measured. Therefore, also the potential benefits of such a screen were determined by the simulation model. The results from these computations are shown in chapter 3.
Besides the unfavourable growing conditions due to temperatures too low, the crop in a Chinese Solar Greenhouse can suffer from high humidities. There are several ways to reduce the humidity of the greenhouse air. These are discussed in chapter 4 and the option used in the experimental greenhouse, which is the injection of warmed outside air, is presented in more detail.

Apart from improvement of the greenhouse climate, large potential improvement on crop production can be achieved by using soilless culture. For this reason, the Chinese Academy of Agricultural Science proposed to grow the crop in the two observed greenhouses on a coco fiber substrate slab. The watering was performed by an automated fertigation unit supplying the water by means of drip irrigation. The experience with this watering system and the fertigation strategy is discussed in chapter 5.
All measurements and control needed for the fertigation, the AHSRS and the screen was performed by a greenhouse climate controller. Chapter 6 shows the technical configuration of this system and the control strategies applied.
Finally, chapter 8 presents the conclusions of this first year of cooperation within the framework of the Sino Dutch Memorandum of Understanding.
1 The Chinese Solar Greenhouse

The Chinese Solar Greenhouse is a widespread applied greenhouse system in the northern rural areas. In almost all cases the greenhouse is completely passive, meaning that it is only heated by the sun. This greenhouse is characterized by a thick wall at the north, east and west side and a transparent south facing curved roof. The greenhouse can be opened for ventilation at the top and at the bottom side. On the top side, the openings are made by pulling apart two pieces of overlapping film of the covering material. If the top-ventilation is not sufficient, the bottom part of the greenhouse can be opened by rolling the foil upwards on a tube.

Figure 1.1 Sketch of a cross-section of a Chinese Solar Greenhouse. The total width of the greenhouse (excluding the base of the thick wall at the northern side) varies between 6 to 10 meters.

The length of this type of greenhouse varies from 30 to some 100 meters and with a cultivation width of 5 to 9 meters, the cropping area ranges between 150 to 900 m². However, the typical size is 1 Mu, which is 400 m². The length of the greenhouse is bounded by practical considerations about internal transport of supplies and product. The width is predominantly limited by outside conditions. The colder the winter conditions, the smaller the width of the greenhouse. This is because the energy harvest and release by the northern wall is limited and by selecting the width of the greenhouse, the total heat loss during the night can be balanced width the energy availability. Therefore a Chinese Solar Greenhouse around Beijing will have a cropping width of about 6 meters, while around Shouguang the cropping width can go up to 8 meters.

The crop is typically grown in the soil, although growing in substrate systems or growing in pots is not exceptional. Fertilizers are predominantly provided by organic or chemical fertilizers added to the soil. Watering takes place by a manual opening of a valve that brings in water, distributed via small ducts along the crop rows. The schedule to open the valve is depending on the outside conditions and the crop development. Another important feature of the Chinese Solar Greenhouse is the heavy insulating blanket, which is stowed on top of the greenhouse during the day and deployed during the night by rolling it down (see figure 1.2).
Stowing and deployment of the blanket is performed manually, often assisted by a motor. It is hardly ever a fully automated process since it needs close human monitoring to protect the vulnerable rolling system from damage. Because of this manual intervention, it is also the grower who decides every day on which time the blanket is stowed or deployed. On dull and cold days, the stowing will be postponed to some hours after sunrise and the blanket will be closed earlier. On warmer or fine days, the blanket can be stowed soon after sunrise.

With a closed blanket after a warm day the greenhouse cools down only slowly (about 2 °C per hour) because of the thermal mass of the northern wall and soil and the high insulation factor of the blanket.

The challenges faced with the Chinese Solar Greenhouse are (1) the inhomogeneity of the temperature in the greenhouse, (2) the very high humidity during the night, (3) the high temperatures in summer and (4) the sometimes much to low temperatures in winter. Also the small size of the greenhouses is a difficulty since it hampers to make advantage of economies of scale.

The Chinese Academy of Agricultural Sciences have placed all these issues on its research agenda and is running projects on the different subjects on various locations. Together with the municipality of Shouguang, work is carried out to prevent the low temperatures and high humidities in winter by exploring the possibilities of the Active Heat Storage and Release System (AHSRS), a system for dehumidification and the application of thermal screens. Within this project with the Shouguang municipality, also topics on soilless cultivation, fertigation, crop handling and computerised control are addressed. The results of the first experiments on the Shouguang experimental station on a new Chinese Solar Greenhouse are presented in the next chapters.
The traditional Chinese Solar Greenhouse does not actively control the temperature in winter. During daytime, the crop, the soil and the thick north wall are heated by solar radiation. During the night the thermal mass of the soil and north wall (and also the east and west walls to a small extent) deliver heat to the greenhouse. This heat release during the night and accumulation of heat during the day cannot be influenced, but one would like to have the possibility to schedule the harvest and release of energy. When postponing the harvest of energy in the early morning, the greenhouse will heat up a bit faster and when postponing the heat release towards the end of the night, the minimum temperature could be somewhat elevated.

The possibility of scheduling the harvest and delivery of energy in order to improve the ambient conditions for the growing crop formed the major reason for the development of the Active Heat Storage and Release System (AHSRS).

The AHSRS consists of vertical panels along the north wall, a pump that circulates water along these panels and a sub soil water storage tank. During daytime in winter, the panels are heated by direct solar radiation. When relatively cold water is circulated over the panels, energy is harvested by means of warmed water. With the circulation rates applied, the temperature lift per passing of the water is small (max. 3 °C), so the water in the tank will warm gradually. After noon, the radiation intensity is going down, and at a certain point the return water becomes colder than the supply water. This is the moment that the pump should be stopped.

In the following night, the temperature of the greenhouse will decrease. When the greenhouse temperature passes a certain threshold, the pump can be switched on again. This will bring warm water onto the panels, which will then act as a surface that heats the greenhouse prohibiting that the greenhouse becomes too cold.

The sketch below shows the working of the AHSRS.

Figure 2.1 Schematic picture of the energy harvest and energy release at the north wall by the AHSRS. The water content of the tank and the capacity of the pump are expressed per m² greenhouse surface.

Figure 2.1 shows some typical figures as observed during operation in the spring of 2015. It was observed that the increment of the water temperature when running along the panel during the energy harvest period is maximal 3 °C. When cooling down, the decrement of the water temperature is smaller. Combined with the relatively high water circulation rate compared to the tank capacity (the entire content is circulated in about one hour) the tank acts as a well-mixed tank. There was no noticeable stratification.
Among other goals, the research project in Shouguang is meant to study the potential of the AHSRS system, but since there are no data on the climate regime in a nearby, generally similar but traditional Chinese Solar Greenhouse, a direct comparison cannot be made. Moreover, due to a large number of delays, the greenhouse with the AHSRS started only after February 10th to work, meaning that the difficult December and January months have become out of scope of the monitoring process. Therefore, the majority of the conclusions on the perspective of the AHSRS system are based on computations with a simulation model, discussed in the next section.

2.1 Simulation of the Chinese Solar Greenhouse with Active Heat Storage and Release System

Due to the lack of measurements, the perspective of the AHSRS will have to be described by simulation results. The simulation model used is developed as an extension of the KASPRO simulation model (de Zwart, 1996). KASPRO is a dynamic model which describes the greenhouse climate based on the greenhouse construction elements, ventilation openings, climate control equipment, covering material and the outside climate of a given location.

The model is based on the computation of relevant heat and mass balances, each in dependence of the physical properties of the simulated entities (e.g. radiation, emission, transmission, heat exchange coefficient and capacity). The heat balances describe the conductive, convective and radiative processes and latent heat associated with condensation and evaporation. The mass balances are constituted from exchange processes through leakage and ventilation, canopy transpiration, evaporation from wet surfaces and condensation at cold surfaces. All state variables are scaled to a m² greenhouse surface.

In order to tailor this model to describe the Chinese Solar Greenhouse, a light absorbing body representing the north wall was added. When describing a traditional Solar Greenhouse, this body is constituted by three thermal masses: one small capacity layer absorbing the solar radiation, a layer with a larger capacity representing the rammed soil that accumulates and releases heat and a third small capacity representing the outer layer of the wall. The three layers exchange heat with each other according to the conductivity of soil and the first and third layer also release heat by convection to the greenhouse air and the outside air respectively. This convective exchange to the outside air contributes for the energy loss at the north side.

Schematically the north wall simulation can be depicted as shown in figure 2.2.

![Figure 2.2](image-url) Schematic picture of the main components added to the KASPRO model to simulate the dynamics of the north wall in a standard Chinese Solar Greenhouse.
The radiation intercepting surface (denoted by Tsurface in figure 2.2.) is assumed to be 2.8 meter high and when the width of the greenhouse is 10 meters, like the case in Shouguang, the radiation intercepting north wall has a total surface of 0.28 m² per m² greenhouse. The energy storing second layer is considered to represent a 0.5 m hollow brick wall, filled with soil. This thickness is derived from the work of Junwei Wang et al. (2014), stating that such a wall thickness is sufficient to provide the dynamic behaviour of the energy storage and release of the north wall. Such a wall of 2.8 meter high will have a heat capacity of about 4.5 MJ/K. This means that, for the Shouguang case, there is 0.45 MJ/K storage capacity in the north wall per m² greenhouse.

The heat capacity of the inner surface (Tsurface) and the outer surface (Toutwall) is set to a value 10 times smaller, so 0.045 MJ/K per m² greenhouse. Thus, the total heat capacity in the north wall in a standard Chinese Solar greenhouse like built in the Shouguang region is about 0.54 MJ/K per m² greenhouse.

The heat exchange coefficient between the surface and the storage layer and between the storage layer to the outwall layer (Toutwall in figure 2.2.) is set to 3.6 W/(m² wall K), which is scaled down to 1 W/K per m² greenhouse surface when considering that each m² greenhouse in the Shouguang case is represented by 0.28 m² north wall.

The heat exchange of the inner wall surface with the greenhouse air is set to 3 W/K per m² greenhouse. The heat exchange with the outside will be much smaller since in common practice all kinds of insulating measures are taken to reduce the heat losses from the outside (straw, mulch, insulating material etc.). Therefore this heat exchange coefficient is set 1 W/K per m² greenhouse, being three times smaller than the heat exchange coefficient at the inner wall.

During the day, a lot of energy is captured by the inner surface of the north wall from direct radiation. When neglecting the effect of shading effects of the north roof (occurring at higher elevations) and the east and west walls (occurring in the morning and afternoon) the radiation to with the North wall is exposed follows from:

\[ I_{\text{north wall}} = \frac{I_{\text{direct}}}{\sin(elevation)} \times \text{trans}_{\text{greenhouse}} \times \cos(elevation) \times \cos(\text{azimuth}) \]  

Where \( I_{\text{direct}} / \sin(elevation) \) gives the direct light intensity perpendicular to the solar beam of radiation, \( \text{trans}_{\text{greenhouse}} \) takes account of the light loss due to the construction and \( \cos(elevation) \times \cos(\text{azimuth}) \) computes the ‘dilution’ of light as a function of the angle of incidence. Neglection of the shade of the north roof gives no problems for the period between November till March. Before November and after March the expression above gives an overestimation of the radiation intensity at the north wall due to the neglection of this shading, but since the focus on research on using solar energy for temperature control in the Chinese Solar Greenhouse is on the cold months, this neglection doesn’t affect the conclusions.

Of course, just like all other fluxes and capacities, the radiation intensity at the north wall has to be multiplied by the north wall to greenhouse area ratio, which is 0.28 in this particular case. In addition, an absorption factor has to be added, contributing for the fact that part of the solar radiation will be reflected by the wall. The absorption is assumed to be 0.8. The transmission coefficient of the greenhouse is set to 0.7.

Besides the absorption of radiation at the north wall, absorption of solar radiation by the crop is an important part of the model. The energy absorbed is partly turned into latent heat for crop transpiration and partly into sensible heat. The division between these two portions is determined by the climate conditions in terms of humidity and temperature and by stomatal reaction of the plant. At high light intensities the stomatal resistance is much smaller than at low radiation intensities. This part of the simulation model was tuned for the evaporative behaviour of a tomato crop.

An typical component of the Chinese Solar Greenhouse is the outside, highly insulating blanket. Because designed to describe a large multispan greenhouse, the KASPRO simulation model omitted such an outside insulating sheet. Therefore, in the current version reduction factors on the heat exchange from the cover to the environment and on the fluxes passing the cover were applied to simulate the insulation by the deployed blanket.

The sketch below shows the fluxes around the cover in the KASPRO model. With the blanket closed the fluxes through the cover (RCrpSky, RFirSky and HAirOut) and the fluxes from the cover (RCovSky and HCovSky) are multiplied by a factor 0.20, resulting in a substantial reduction of the heat losses. Especially the reduction of RCovSky and HCovOut have a large effect on the heat loss, since RCrpSky and RFirSky are often 0 already due to the negligible transmission of thermal infra-red radiation through the foil when wet.
The reduction factor chosen was a result of tuning the model with the measured greenhouse climate data from the Shouguang greenhouse in the period from February 10th till March 24th 2015.

The KASPRO simulation model is equipped with a virtual version of a modern greenhouse climate controller that can control heating, ventilation, dehumidification, carbon dioxide supply etc. However, for the Chinese Solar Greenhouse there is hardly anything to control. Only when the temperature of the greenhouse is higher than 25 °C, the model ‘opens’ the ventilation openings to limit the temperature. With this setting, the actions of the grower are mimicked, although in practice the grower will not react very accurately on the greenhouse temperature.

Also, the model controls the status of the outside blanket (deployed or stowed) and, in the simulations with an inside thermal screen (see chapter 3), also the internal screen. Furthermore, when simulating the AHSRS, the model switches the pump that brings water from the storage tank to the panels, either when the panels are warmer than the water in the tank (daytime), or when the greenhouse becomes too cold (night time).

The result of a KASPRO simulation is a file with data that describe the average of any of the computed variables over a time interval. Typically the greenhouse climate in terms of light, temperature and humidity is sent to the output file and often also the actions of the controller in terms of ventilation, screen deployment, pumps etc.

The time-interval between the data lines is typically an hour, but can be reduced to two minute-intervals or enlarged if required.

**Change of the model when using the AHSRS**

In case the model describes a greenhouse with a AHSRS, the heat capacity of the front layer and the heat exchange coefficient to the greenhouse air are considered to be the same as for the standard Chinese Solar greenhouse, but the capacity of the thick second layer is replaced by the capacity of the water in the tank. As shown in figure 0.1, this tank has a water content of 10 liter per m² greenhouse, with a heat capacity of 0.04 MJ/K per m² greenhouse. The tank is built from a brick wall, so the thermal mass will be somewhat larger than the thermal mass of the water. For the current Shouguang greenhouse, the heat capacity of the storage system is set to 0.05 MJ/K per m² greenhouse. This means that the capacity available to store energy for the levelling of temperatures between day and night in the back wall of the greenhouse with AHSRS is about 10 times smaller than in a standard Chinese solar greenhouse.
An even more important difference between the standard Chinese Solar Greenhouse and the greenhouse with AHSRS is that the heat exchange between the front surface and the heat storage system in the latter case can be switched on and off. With the pump on, the heat exchange coefficient between the North wall front panels and the subsoil water tank is set to 9.3 W/(m² K). This follows from a pump capacity of 8 litre per m² greenhouse per hour (see Figure 2.1) meaning $8 \times 4.18 \times 3600 = 9.28$ W/(m² K). With the pump switched off, the heat exchange is of course 0.

![Image](image.png)

**Figure 2.4** The north, east and west wall of the experimental greenhouse with Active Heat Storage and Release System are heavily insulated with 2 times 10 cm of polystyrene.

The losses from the north wall to the outside for the case with an AHSRS are neglected because the north wall is built from highly insulating material (see figure 2.4). However, the sub-soil heat storage tank is assumed to have a heat loss of 0.02 W/(m² greenhouse K).

The radiation to with the North wall is exposed is not affected when installing the solar panels, but the surface of the panels is smaller than the surface of the back wall. As can be seen in figure 2.4, the panels cover 80% of the width of the north wall and 70% of the height of the wall, which means that only 56% of the radiation can be collected by the panels. The remainder will be (partly) absorbed by the wall, but cannot be transported to the buffer system.

To account for this lowered absorbing surface. This is expressed in the following equation.

\[
I_{\text{panels AHSRS}} = I_{\text{northWall}} \times 0.56
\]

and

\[
I_{\text{north wall AHSRS}} = I_{\text{northWall}} \times 0.44
\]
2.2 Comparison of measurements and simulation.

To tune the simulation model to measured data, ideally measurements from November till March have to be used. In this period of the year, the outside temperatures are low and measures like screens and heat storage will have their largest effects. Unfortunately, only from the very last part of the winter data are available since the measurements started to run at February 10th. The measuring period ranged till May 11th, but as the non-measured manual actions of the grower in opening and closing of the ventilation opening become a more and more important factor in the greenhouse climate only the first 10 weeks are used for the model tuning. The graph below shows the outside temperature and radiation in the period from February 10th till April 20th.

Figure 2.5 The north wall is only covered for 56% by the solar panels.

Figure 2.6 Outside temperature and radiation conditions in Shouguang. The radiation is expressed in the common horticultural unit (J/cm²).
The outside weather data show that in the first weeks the temperature drops well below zero quite frequently. The bottom graph shows that the majority of days are clear, resulting in high daily radiation sums. It are these clear weather conditions that provide the energy for the substantially elevated temperatures in the Chinese Solar Greenhouse.

When running the KASPRO simulation model, after having made the alterations as presented in the former section in order to describe the Chinese Solar Greenhouse with AHSRS, the course of greenhouse air temperatures shown in figure 2.7 was obtained. For this computations, the period of opening and closing the outside blanket were determined by a careful study of the temperatures measured. Deployment of the blanket can be noticed by a sudden increment of temperature at the end of the day. Stowing of the blanket gives a clear sudden decrement of temperature in the morning.

The graphs in figure 2.7 show that the computed temperatures match the data quite well for most of the time, but there are also a number of days where the simulations differ very much from the measurements. There are a large number of reasons for these large differences.

The first is that the ventilation of the greenhouse is operated manually. Therefore it needs a lot of guessing when the sheets on the ventilation openings are opened and to what extent. On average, ventilation is applied when the greenhouse temperature exceeds 25 °C, but when analysing the data it was clear that on some days (the first days for example), much higher temperatures were accepted. On other days, like 27th February, the greenhouse seemed to be ventilated much more in order to keep the temperature around 22 °C. From the interruptions in the green line it can be seen that there are missing data every now and then.

Missing data are caused by a greenhouse climate control computer switched off, which means that in periods without data on the greenhouse climate, also data on the outside weather are missing. Since the greenhouse simulation model cannot run without outside weather data, the gaps had to be filled. This was done by using the data measured at Qingdao airport, the most nearby weather station from which data can be obtained easily. In general, the weather at Qingdao airport is comparable to the weather in Shouguang, but on a daily base there can be some difference of course. The difference between the Qingdao weather and the actual weather conditions in Shouguang may have an effect on the following day since AHSRS and especially soil temperatures have a reasonable time lag.
Figure 2.7 Simulated (blue) and measured (green) greenhouse temperature. Each graph shows a period of two weeks and the 5 subsequent graphs span a period of 10 weeks.
The simulation model also computes the relative humidity of the greenhouse air. Figure 2.8 shows the results of the comparison between measured and computed relative humidity. Most of the time, the simulated air humidity is close to the measured humidity, but also here on some days the difference is very large. This is especially the case for the last week simulated.

*Figure 2.8* Simulated (blue) and measured (green) relative humidity in the greenhouse. Each graph shows a period of two weeks and the 5 subsequent graphs span a period of 10 weeks.
The Active heat storage and release system is simulated quite well, although the data set has only a very few occasions where the system actually releases heat. The graph in figure 2.9, shows the measured and simulated temperature of the water that runs off from the solar panels. When the pump is switched off, the return water line runs dry, resulting in an incorrect sensor readout. Therefore, only values are shown when the circulation pump is running. The pump runs during charging and during discharging of the AHSRS. Charging will be during the day, and discharging during the night. In the graph, spanning 20 days, the periods of discharging are explicitly marked. It shows that there are only three nights in which the storage system was really being discharged. This is because from the moment that the experiment started, the greenhouse never became very cold.

![Figure 2.9 Simulated (blue) and measured (green) outgoing water temperature from the panels from February 10th till March 1st.](image)

The picture below shows the measured and simulated data of March

![Figure 2.10 Simulated (blue) and measured (green) outgoing water temperature from the panels in March.](image)

Also in this period in March there were only three nights where the heat storage tank was actually discharged. Figure 2.10 shows some subsequent days with a good match, but also a period with more than 5 °C difference between measured and simulated data. With the limited amount of data, and also the uncertainty of the actual amount of water in the storage tank (the tank was leaking and was replenished weekly with an unknown amount of water) no further attempts were made to further tune the model for the AHSRS.
In order to run the simulation from which the results are shown, the on and off switching of the pump was synchronized with the switching of the pump in the experiment. The graph shows that some improvement in the control can be achieved when the pump would have been switched off whenever the temperature starts to go down. From figure 2.10, which is a magnification of the data February 13th and 14th, it can be read that the temperature of the water that runs off from the panel starts to decrease around 15:00, so well before sunset. It shows that about 2 to 3 °C of the 10 to 12 °C increment in water temperature gained during the harvest period is already lost in the last running hour of the day. The graphs shows that there is some offset between simulation and measurement, but that the dynamics are matching.

**Figure 2.11** Simulated (blue) and measured (green) outgoing water temperature from the panels from February 13th and 14th.

Unfortunately, the model for the traditional Chinese Solar Greenhouse, without the AHSRS system, as discussed around figure 2.2, could not be compared with measured data since all four compartments that were monitored by the greenhouse climate computer were built the same way, meaning thin insulating walls with a very small heat capacity and the AHSRS to provide the thermal mass. Therefore, the effect of the AHSRS, presented in the next section is based on simulation only.

### 2.3 Effect of the AHSRS

The effect of using the AHSRS on the temperature in a Chinese Solar Greenhouse is analyzed by using the simulation model with one of the two model descriptions of the heat storage as presented in section 2.1. For both simulations, the amount of radiation to which the north wall is exposed is equal, just as the heat exchange coefficient from the North wall to the greenhouse air, being 3 W/(m² greenhouse K). Note that this heat exchange coefficient is a simplification of the actual situation where the heat exchange consists of a convective and a radiative part.

In case the simulation is run for a standard Chinese Solar Greenhouse, the north wall exchanges heat with the large thermal mass behind the north wall in an uncontrolled way. Only temperature differences determine if heat is accumulated or released from the thermal mass.

In case the model runs the AHSRS case, 56% of the radiation to which the north wall is exposed is absorbed by the solar panels. The remaining 44% is absorbed by the surface around the panels and released to the greenhouse air since the heat capacity of the North wall of the AHSRS greenhouse is very small and the insulation is very high.

The solar panels will heat up by the energy input of the sun and whenever the temperature of the surface is higher than the temperature of the water in the storage tank, the pump will be switched on to store the energy excess in the heat storage tank. In fact, the control strategy applied is more advanced than the control used in the actual greenhouse because the actual greenhouse omits temperature sensors in the storage tank and at the solar panel. The strategy applied in the model avoids the temperature losses in the afternoon which are shown in figure 2.11.
In both simulations, energy losses from the storage system are taken into account, as described in section 2.1. As discussed previously, the deployment of the insulating blanket is a very important characteristic of a Chinese Solar Greenhouse. In section 2.2, the deployment of the blanket was derived from the actual deployment as observed from the measured data. In this section, however, the working of the AHSRS in a period from which no data on blanket deployment are available. Therefore, some reasonable description of the actions taken by a grower were derived.

It appeared that deployment of the blanket according to the following formula resulted in an automatic deployment comparable to the manual deployment observed in the period for February 10th till May 1st.

\[
\text{If } (\text{tout} < 12) \\
\quad \text{IglobCrit} = 10 \times (14 - \text{tout}) \\
\quad \text{If } (\text{Iglob} < \text{IglobCrit}) \\
\quad \quad \text{Deploy blanket} \\
\quad \quad \text{Else} \\
\quad \quad \quad \text{Stow blanket} \\
\quad \quad \text{EndIf} \\
\quad \text{Else} \\
\quad \quad \text{Keep blanket stowed} \\
\quad \text{EndIf}
\]

This piece of code tells that the blanket is not used when the outside temperature stays above 12 °C. When the temperature drops below 12 °C, the blanket is deployed when the outside radiation drops below a certain threshold. This threshold is increased as the outside temperature goes down. In practice this means that as the outside temperatures drop, the blanket will be deployed earlier in the afternoon and will be opened later in the morning.

The graph below shows the comparison of the blanket deployment as computed by the formula mentioned and the actual deployment observed in February 10th till April 1st.

The computed amount of hours with a deployed screen matches quite well with the observed behavior in the first weeks, which are the coldest weeks. In later weeks, the automated control gives less hours of deployment. However, since the study of the behavior of the AHSRS concentrates on the cold period, the underestimation of the deployment of the outside blanket is not worth further tuning, especially because the actual behavior of the grower will never meet the crisp reasoning of a formula.

The formula tells that at a temperature of 12 °C, the blanket will be deployed when the outside radiation is below 20 W/m². At 0 °C, the outside blanket will be deployed below 140 W/m² of outside radiation and when it is -10 °C, the blanket will be opened when the outside radiation is below 240 W/m².

The graph below shows the simulation results of the daily average greenhouse air temperature for the standard Chinese Solar Greenhouse and the Chinese Solar Greenhouse with AHSRS.
**Figure 2.13** Diurnal average greenhouse air temperature of a standard Chinese Solar Greenhouse (blue) and a Chinese Solar Greenhouse with AHSRS (green). The simulation uses the weather data from Qingdao (except for the period from February 10th till May 15th for which the Shouguang weather data were available). The data are smoothed with a 4 days moving average filter to improve readability of the graph.

The graph shows that in autumn and spring the greenhouse with AHSRS is about 2 degrees colder than the reference greenhouse, but that in the winter months the AHSRS greenhouse is slightly warmer. The lower temperatures in autumn and spring are a result of the smaller heat capacity of the greenhouse with AHSRS. This makes that the greenhouse warms more quickly during the day, which results in an earlier opening of the ventilation openings and, with that, a loss of energy.

In winter, the average temperature of the greenhouse with AHSRS is higher because of the improved insulation of the north wall (see figure 2.4). During the day the temperature of 25 °C is hardly ever reached so the ventilation openings stay closed.

**Figure 2.14** Average course of the greenhouse temperature in a 24 hour period in November (left) and in December (right) for a standard Chinese Solar Greenhouse (blue) and a Chinese Solar Greenhouse with AHSRS (green).

The effect of the smaller heat capacity of the greenhouse with AHSRS can be seen in the left graph of figure 2.14. In this graph, the average diurnal course of the greenhouse temperature is shown. This means that every point in each line gives the average value of the 30 temperatures simulated for that time instance in November. The green line has clearly steeper slopes than the blue line, both upward and downward. Also it can be seen that the green line passes the criterion for ventilation (25 °C) earlier and longer, meaning that the greenhouse with AHSRS ‘throws away’ more solar energy than the standard Chinese Solar Greenhouse.

In December, the right hand graph in figure 2.14, the greenhouse temperature doesn’t exceed the ventilation threshold anymore. Then, due to the better insulation of the east, west and north wall, the heat loss of the greenhouse with AHSRS is less and therefore the average temperature is higher.
The right hand graph in figure 2.14 also shows that the minimum temperature in the early morning in the greenhouse with AHSRS is higher than that of the standard greenhouse. This elevated minimum temperature is at the expense of a lower temperature in the evening and can only be achieved by postponing the release of heat accumulated in the buffer till the greenhouse really gets cold (12 °C in the applied model settings).

Figure 2.15 shows that for most of the nights in winter the minimum temperature of the greenhouse with the AHSRS is about 2 °C higher than the minimum temperature of a comparable standard Chinese Solar Greenhouse in the Shouguang region. Only in the last days of January, the coldest days of the year, the minimum temperature in both the greenhouses is equally low. This is caused by the combination of low outside temperatures and the low daily radiation sum.

![Figure 2.15 Minimum temperatures as computed for a standard Chinese Solar Greenhouse (blue) and a Chinese Solar Greenhouse with AHSRS (green). Weather data hold for the Shouguang region.](image)

Figure 2.16 shows that the last week of January has a number of days with a radiation sum well below 5 MJ/(m² day). The same week happens to have low minimum outside temperatures (-8 °C) and this combination results a shortage of solar energy, both in the standard greenhouse as in the greenhouse with AHSRS.

![Figure 2.16 Minimum temperatures as computed for a standard Chinese Solar Greenhouse (blue) and a Chinese Solar Greenhouse with AHSRS (green) and the daily radiation sum (red) in January 2015 in the Shouguang region.](image)

The results of the simulations give rise to the conclusion that the increment of the minimum temperatures in the cold months of the year as observed for the greenhouse with AHSRS are caused by the increased insulation of the north wall and not a as a result of the controllability of the heat storage and release. When the heat loss to the outside for a standard greenhouse, in section 2.1 estimated on 1 W/(m² greenhouse K) is lowered to 0.25 W/(m² greenhouse K) the minimum temperatures of the 'standard' Chinese Solar Greenhouse in the coldest months have become equal to the minimum temperature of the Chinese Solar Greenhouse with AHSRS. This can be read from figure 2.17.
A heat exchange coefficient to $0.25 \, W/(m^2_{\text{greenhouse}} \, K)$ between the outer layer of the north wall to the outside means a heat exchange coefficient to $0.25/0.28 = 0.9 \, W/(m^2_{\text{north wall}} \, K)$. Such an insulation factor can easily be achieved by adding a layer of polystyrene onto the outside face of standard rammed soil north wall.

**Figure 2.17** Minimum temperatures as computed for a Chinese Solar Greenhouse with an insulated outside face of the northern wall (blue) and a Chinese Solar Greenhouse with AHSRS (green) for the Shouguang region.
3 Energy screens

When the insulating blanket is deployed, the greenhouse becomes completely dark meaning that photosynthesis and crop production stops. This means that in the early morning or in the early evening the grower will have to make a difficult choice between light in the greenhouse with a low insulation, or a high insulating, but dark greenhouse.

Since a too low temperature is also disadvantageous, in winter the blanket is deployed quite early in the afternoon and stowed quite late in the following morning.

The addition of a moveable transparent screen to the greenhouse might provide a solution.

The picture below shows the construction of this thermal screen. It consists of three sections of the Ludvig Svensson Luxous screen, running along the full length of the greenhouse and sliding up and down along pulling wires. One motor drives the three sections together.

![A moveable screen in a Chinese Solar Greenhouse, consisted of three equal sections opened and closed by one motor. When stowed, like on this picture, the screen is folded to an as small as possible package](image)

Unfortunately, the screening system was not operational during the cold months of the current experimental period (February and March). Therefore, just as for the working of the AHSRS, the performance of the screening system can only be determined by the simulation model.

Figure 3.2 shows the results of a calculation of the effect of the moveable thermal screen in case this screen would be controlled exactly the same as the outside blanket. This means that whenever the outside blanket was deployed, the thermal screen was deployed and when the blanket was stowed, the thermal screen was stowed. When looking at the diurnal mean temperatures the effect of the additional screen can clearly be seen in the cold months of the year. The mean temperature is then increased by about 0.8 °C.
When looking at the daily minimum temperature, of course the effect of the moveable screen is more distinct. In Figure 3.3 it appears that on the coldest days, the additional insulation by the thermal screen is expected to yield a 1.5 °C temperature increase. The lowest temperature in January will be 7.5 °C instead of 6 °C.

![Graph of daily minimum greenhouse temperature](image1)

**Figure 3.2** Diurnal mean greenhouse temperature in a standard Chinese Solar Greenhouse (blue line) and a Chinese Solar Greenhouse with a moveable thermal screen that is deployed parallel to the outside blanket (green). For a better readability, the data were smoothed with a 4 days moving average filter.

![Graph of greenhouse temperature](image2)

**Figure 3.3** Daily minimum greenhouse temperature in a standard Chinese Solar Greenhouse (blue line) and a Chinese Solar Greenhouse with a moveable thermal screen that is deployed parallel to the outside blanket (green). For a better readability, the data were smoothed with a 4 days moving average filter.

When using the moveable thermal screen in combination with the Active Heat Storage and Release System, the effect of the screen becomes slightly bigger. This can be seen in figure 3.4. The reason is the smaller amount of energy available due to the reduced thermal mass, as discussed in chapter 2 and in case of larger limitations on energy availability, the additional insulation has a larger effect.

![Graph of greenhouse temperature](image3)

**Figure 3.4** Daily minimum greenhouse temperature in a Chinese Solar Greenhouse with Active Heat Storage and Release System (blue line) and in the same type of Greenhouse equipped with a moveable thermal screen that is deployed parallel to the outside blanket (green). For a better readability, the data were smoothed with a 4 days moving average filter.
The major advantage of a thermal screen like the Ludvig Svensson Luxous screens is the transparency. As the screen provides additional insulation when deployed, the period with a deployed outside blanket could be shortened. In this way, the greenhouse temperature in a greenhouse with a transparent moveable thermal screen will transmit more light to the crop without lowering the temperatures in the greenhouse.

To evaluate the possibilities, the criterion on which to deploy the outside blanket was changed. The graph below shows the standard closing behaviour to deploy the outside blanket, as discussed in section 2.3, and a new control of the blanket resulting in a postponed deployment in the evening and advanced stowing in the morning.

![Figure 3.5](image1.png)

**Figure 3.5** Graphical representation of the criterion to deploy or stow the outside blanket. In the reference greenhouse the blanket is deployment when the combination of temperature and radiation lies below the blue line. For the greenhouse with moveable screen the outside blanket is deployed when the conditions are below the green line.

The advantage of the reduction of the number of hours with a deployed outside blanket is of course the increased availability of light for the crop. The figure below shows the average deployment of the outside blanket in the standard situation and the alternative deployment in a greenhouse with a thermal screen (left) and the resulting greenhouse temperature (right).

![Figure 3.6](image2.png)

**Figure 3.6** Average course of the deployment of the outside blanket and the screen in December (left) and the resulting average course of the temperature (right). In both cases a Chinese Solar Greenhouse without an AHSRS was used for the simulation.

In the left hand graph of figure 3.6 it can be seen that the thermal screen in the simulation including the thermal screen (red line) follows the deployment of the outside blanket in the reference computation (blue line) and that the deployment of the outside blanket is postponed in the afternoon and that the stowing is advanced in the morning (red line).
In December, the number of hours with a deployed outside blanket goes down from 517 hours to 450 hours, which means that the thermal screen allows for slightly more than two hours of additional day length per day. The right hand graph of figure 3.6 shows that the average and minimum temperature in the greenhouse with a thermal screen is still higher. Only at the end of the day, the postponed deployment of the outside blanket results in a somewhat lower temperature, but this temperature decrement is compensated during the rest of the day. The reduced number of hours with a deployed outside blanket gives a slight increment of the total amount of light in the greenhouse during the cold period. On average, for December and January, the increment is 1% and for November and February the increment is 0.5%. The extra amount of light is very small because the difference in deployment of the outside blanket takes place at the boundaries of the day period. This period has typically low light intensities and therefore contribute only a little to the daily amount of light. Moreover, the thermal screen does intercept light when it is deployed, but also when it is stowed. This can be seen in figure 3.1. Therefore, despite the reduced number of hours with a deployed outside blanket, the thermal screen reduces the total amount of light in the greenhouse during the growing period as a whole with about 2.5%.

In the actual greenhouse in Shouguang, the light interception of the thermal screens will be even more since the driving mechanism omits the friction sliders that enable a tight stowing of the screen package (see figure 3.7).

*Figure 3.7* Actual fixing of the end profile of the screen deployment mechanism (left) and best practice fixing with friction sliders (right).

Because of the rigid fixation of the end profile on the pulling wire, the screen motor the stows the screen has to stop quite early to prevent that the pulling wires break at points with the tight most fixing to the pulling wire. Since the rigid fixation points in the greenhouse will never be exactly parallel (and subject to thermal expansion and contraction), quite some tolerance is needed to achieve this, especially since the pulleys in the greenhouse were poorly aligned. This poor alignment can be improved, but the tight fixation would better be replaced by friction sliders as shown in the right photo of figure 3.7. With such friction sliders, the path of the pulling wire can be made 5% longer than the average distance between a deployed and a stowed screen. This will result in a tight deployment and stowing, irrespective the building tolerances.
4  ppHumidity control

When looking at figure 2.8, showing the humidity of the greenhouse, it is clear that the humidity grows to very high values every night. This is because of the large temperature drop in a greenhouse with hardly any ventilation and a crop and soil that continues to produce vapour. In ordinary practice the humidities will be even higher since the new crop in a Chinese Solar Greenhouse is normally planted in September or October. This means that normally the crop in February and March will be mature, giving higher rates of evaporation than in the experiment shown here. A full grown crop in a greenhouse with hardly any ventilation or condensation, which is a result of deploying the blanket, will give humidities well over 90% for many nights. Since the experiment did not provide data from the winter period with a full grown crop, simulated data are used. The figure below shows the computed humidity during the second part of the night (from 0:00 till 06:00) and the humidity during the day (defined as the period with more than 10 W/m² outside radiation).

![Figure 4.1 Simulated humidity of the greenhouse air during the second half of the night (00:00 till 06:00) (blue) and during the day, defined as the period with more than 10 W/m² of global radiation (green).](image)

In the beginning of the growing period, assuming that the new tomato crop is transplanted on September 15th, the humidities are generally low, especially during the day. This is because the crop starts as a small plant. Then, in November the humidity becomes higher since the growing crop reaches its full evaporative capacity. Moreover, the greenhouse will be ventilated less because of the decreasing outside temperature. In December and January, especially the daytime humidity is high. During the day, the crop evaporates, but the greenhouse is kept closed. During the night in this period the humidity is typically somewhat lower than in the preceding and following months because the small air exchange with the outside air through leakage will already carry off some 10 grams of moisture per m² per hour due to the very low absolute moisture content of cold outside air. In spring, the absolute moisture of the outside air will increase with temperature and the contribution of the leakage to moisture removal decreases, with an increase of the night time humidity as a consequence.

High humidities are considered as a risk for the crop because fungal diseases tend to spread more easily in humid conditions. Therefore, in most greenhouses, vents are not only opened at temperatures too high, but also when the humidity passes a certain threshold. Some growers are already opening their vents when the humidity exceeds 80% relative humidity. For vegetables a threshold of 85% is commonly used, but for greenhouses with a homogeneous temperature distribution a relative humidity of 90 to 92% is acceptable as well. The problem with the Chinese Solar Greenhouse, however is that the ventilation openings are covered when the insulating blanket is deployed. Since the need for dehumidification is concentrated in the night period with the blanket deployed, an alternative way of dehumidification had to be developed.

Dehumidification of greenhouses can be carried out along two main routes. The first, and most simple, is the exchange of greenhouse air with outside air. Opening vents, like discussed in the former paragraph is an example of this principle, but also blowing air into the greenhouse or dragging air out of the greenhouse by mechanical ventilation is based on the same principle. Air exchange with outside only provides dehumidification if the absolute moisture content of the outside air is lower than the absolute moisture content of the greenhouse air. In places with a continental climate, like Shouguang, this will almost always be the case.
The second principle is to use internal dehumidification by means of condensation on an artificially cooled surface in a heat exchanger. When this heat exchanger is cooled by a heat pump, the latent heat added to the cold surface with the condensation process can be used directly, or after temporary storage, to heat the greenhouse. Heating will often be necessary because together with the extraction of moisture, the cold heat exchanger extracts sensible heat as well, which may result in an unfavourably low air temperature. In the work of DeZwart (2014), an extensive description of such a system is given. The second system is very energy efficient, but expensive in terms of investment, being of around 75 RMB per m². Such investments were considered not to be applicable for the Chinese Solar Greenhouse. Therefore, the first system was used and 2 out of 4 of the experimental greenhouse compartments of the Chinese Academy of Agricultural Science on the Shouguang experimental station were equipped with a simple dehumidification system based on the exchange of outside air with inside air. The sketch below gives an impression of the system applied.

![Distribution duct, Fan and heater housing (underground), Air inlet (outside)](image)

**Figure 4.2** A duct system that brings dry outside air into the greenhouse and distributes the air evenly along the length of the compartment (in the actual building is was the east compartment of each of the greenhouses that was equipped with this system instead of the west compartment as shown here).

As it is outside air blown into the greenhouse, on many nights in winter this air will be freezing cold. If blown unheated, this will harm the crop in the surrounding of the distributing duct, especially at the side closest to the inlet. Therefore the air has to be heated. For the sake of simplicity this heating is carried out with electrical heaters. The picture below shows a sketch of the fan that directs the air to the greenhouse compartment and the three electrical heaters placed in the sub-surface housing of the dehumidification system.

![Fan, 3 heaters, Air inlet, Distribution duct](image)

**Figure 4.3** Sketch of the heaters and fan in their sub-surface housing.
When on, each heater gives a heating power of 2 kW. The air supply system has a capacity of 3 m³ per m² per hour, and with a greenhouse surface of 440 m², the fan blows 3*440 = 1320 m³/hr into the greenhouse. A 2 kW heater in a 1320 m³/h air flow gives a temperature increment of 4.5 °C. By switching on one, two or three heaters, the greenhouse climate controller can bring the air blown into the greenhouse close to the actual greenhouse temperature.

When all three heaters are on, the air passed to the distribution duct can be 13.5 °C warmer than the air at the inlet and because the temperature in Shouguang hardly ever drops below -10, the heaters provide a good prevention to frost. However, already at temperatures below -5 °C, the air blown into the greenhouse will be quite cold. For such very cold days, the temperature of the air blown into the greenhouse can be kept at a reasonable level by restricting the inlet to reduce the capacity to 2 m³/(m² hr).

Figure 4.4 shows the implementation of the air distribution duct and the sub-surface heaters and fan in the Shouguang greenhouse. The distribution duct was made of a polyethylene foil slurve with a diameter of 40 cm. In the foil, every 20 cm two holes with 14 mm diameter were punched. This configuration of number of holes, size of the holes, diameter of the slurve and its length of 43 m makes that the distribution duct will give the 1320 m³/hr at a pressure of 45 Pa. Moreover, the outflow of air will be equal along the length of the slurve within + or – 5%.

The slurve was mounted by putting a supporting wire through the slurve and wires that fix the supporting wire to the greenhouse construction.

The height of the supporting wire was chosen such that a deflated slurve just doesn’t reach the soil surface.
Unfortunately, the capacity of the electricity grid of the Shouguang experimental station during the experiment was too small for the 6 kW heating power so the dehumidification system has not been used in this first experimental period.

Just as for the evaluation of the working of the AHSRS and the thermal screens, the KASPRO simulation model was used to evaluate the expected effect of the dehumidification system installed. Figure 4.5 shows the results of this

![Figure 4.5](image)

**Figure 4.5** Simulated humidity of the greenhouse air during the second half of the night (00:00 till 06:00) (blue) and during the day (green) after implementation of a dehumidification system with an air supply capacity of 3 m³/(m² hr). The model switches the dehumidification on when the humidity exceeds 90%. The thin lines hold for the case without dehumidification and are copied from figure 4.1.

Obviously, the system with a capacity of 3 m³/(m² hr) prevents the high humidities and is expected to keep the humidity below 90% RH almost all the time. The dehumidification system will run at part-load quite often. From the cumulative frequency curve, shown in figure 4.6, can be read that the dehumidification system will run at full capacity for about 400 hours per year. The rest of the year the system will reduce the dehumidification capacity by means of a an on/off sequence in time (e.g switching on when the humidity exceeds 91% and off when it drops below 89%).
Figure 4.6 Cumulated frequency curve of the air exchange capacity of the dehumidification system when used to limit the humidity to 90% RH.

The simulation model computes the amount of electricity used by the heaters to raise the outside temperature to the greenhouse temperature when using the dehumidification system. This appeared to be 6.7 kWh/m² per year and would mean a yearly electricity consumption for heating of about 3000 kWh per greenhouse compartment of 440 m².
5 Soilless cultivation

In the long agricultural history crops are grown in the soil. The soil provides a storage system for water and nutrients and provides the physical body for anchoring the plants. However, for high value crops like flowers and vegetables there is a clear tendency towards soilless cultivation, sometimes also referred to as hydroponic growing systems. The major reason for getting crops out of the soil is the decrement of the infestation of soil borne diseases and the improved controllability of the nutrient supply. Also leaching of nutrients, which means a loss of fertilizers, environmental pollution and water loss can be prevented or at least strongly reduced when using soilless cultivation.

The major characteristic of soilless cultivation is the small storage capacity of water and fertilizers. Plants growing in potting bags get shots of about half a litre of water per irrigation event. Plants grown on rockwool or coco fibre slabs get shots of about 100 cc water and since the amount of water evaporated by the plants will be essentially the same, the frequency of the watering shots will be higher (5 times higher in this particular example). Aeroponic systems, where the roots are wetted by spraying of water, are at the extreme end of the spectrum, needing a continuous water supply.

Besides the advantage of a soilless cultivation, the examples above show that the gain of a better controllability of the root zone has its price in a growing vulnerability of the watering system. On a sunny day, a failure of the water distribution when growing in potting bags has to be repaired in about half a day. When growing on rockwool or coco fibre slabs a malfunctioning water supply should be repaired in about an hour and aeroponic systems will need immediate repair.

The vulnerability of the system means that, when switching to a soilless cultivation system, spare parts of the most crucial components of the watering system, being the pump and the valves, have to be available. Also, a backup power generator needs to be stand by for the case that the power grid fails. The backup power needs to have a capacity large enough to run the irrigation pump.

The Shouguang greenhouse did not have such a back-up generator stand by and this has led to serious water shortage on April 25th. At that day there was a power failure in the whole area. Despite the hard work of the greenhouse personnel the crops wilted seriously in the afternoon and the disruption of power supply led to the loss of about half a cluster per plant on average.

The general principle of a soilless cultivation system is that the rooting medium is considered not to have nutrients, meaning that all nutrients are supplied and can, therefore, be controlled. The basic scheme is shown in the picture below.

![Figure 5.1 General principle of a soilless cultivation system.](image-url)
The sketch of figure 5.1 shows a mixing unit that prepares a storage tank with irrigation water. When filling this tank, a certain composition of nutrients is mixed with fresh water to get a prescribed recipe-EC. The EC (electro conductivity) of a fertilizer solution is a measure for the salt content and therefore for the osmotic value of the irrigation water. The higher the EC, the more abundant the availability of nutrients, but the more difficult for the plant to acquire the water for transpiration. Typically the EC of irrigation water for vegetables in a soilless system is between 2.5 and 5 mS/cm (which is an equal unit as dS/m).

The intermediate storage tank sketched in figure 5.1 helps to provide back-up capacity, but is not principally needed. The Shouguang greenhouse did not have such a storage tank, so the total fertigation system is shown in this picture below (figure 5.2).

![Figure 5.2 The mixing- and supply unit in the Shouguang greenhouse.](image)

The three red containers shown in figure 5.2 are the storage vessels for the A-component of the concentrated fertilizer composition, the B-component of the concentrated fertilizer composition and the storage tank for the acid-solution (sulphuric acid). The concentrated nutrients are divided over two tanks to keep the Ca\(^{2+}\) and SO\(_4^{2-}\) ions separated. Combining these ions in a concentrated solution would result in the formation of insoluble gypsum.

Normally, the nutrients in the stock solution are 100-times concentrated, which means that after adding 98 litre of fresh water to 1 litre of A and 1 litre of B results in the required nutrient solution.

A standard nutrient composition for tomato grown in rockwool, for example reads:

![Figure 5.3 An example of a nutrient composition for a tomato cultivation in rockwool.](image)
Suppose one wants to prepare a stock solution for the mixture of 40 m³ of irrigation water, which will be the water consumption of the 4 compartments in a week time. Assuming a concentration factor 100 means that the mixing unit will dilute 400 litres of A and 400 litres of B and that the amount of fertilizers to be applied in this period will have to be put in the A and B tank. When taking the Ca as an example, 40 m³ of water with 7 mmol of Ca per litre means that 280 moles of Ca is going to be supplied with this water. Ca is normally applied with the A component of the stock solution and when this is supplied in the form of 5[Ca(NO3)2.2H2O].NH4NO3, which is a less hygroscopic calcium nitrate fertilizer, 60.4 kg of this fertilizer will have to be diluted in 400 litres of water in the A-component stock solution tank.

The figure below shows the complete mixture of the nutrient solution for 40 m³ of fertigation water resulting in the nutrient composition shown in figure 5.3, after a 100-times dilution. It can be seen that the Potassium Nitrate is added to both the A and the B tank. By dividing the total of 23.5 kg of Potassium Nitrate over the two tanks, the total amount of fertilizer in both tanks can be kept the same and therefore the density of the liquid.

![Table of Nutrient Compositions](image)

**Figure 5.4** Example of a recipe for a stock solution composition that results in the nutrient composition shown in figure 5.3 after a 100-times dilution. The quantities of fertilizers are enough for 40 m³ of irrigation water.

When the greenhouse climate controller gives the command to start the irrigation, the mixing unit starts to pump water to the drippers while, at the same time, taking in fresh water and adding the concentrated nutrient supply. The addition of concentrated nutrients is realized by the dosing pumps (see figure 5.2) and the on/off switching of these pumps is based on the measured EC of the water in the mixing tank. When the EC is set to 3.5, the pumps are switched on when the EC drops below 3.4 and switched off when the EC exceeds 3.6. Of course, this hysteresis can be set by a parameter in the climate computer.
Apart from the control on EC, the mixing unit can also lower the pH if necessary. This is done by adding acid from the third container, while measuring the pH.

Figure 5.5 shows the mixing unit in action.

![Figure 5.5](image)

**Figure 5.5** During the mixing process, fresh water is mixed with concentrated stock solution of fertilizers. When the nutrient stock solution is prepared based on a concentration factor 100, there will be 98 litres of fresh water mixed with 1 litre of concentrated nutrients from the A-vessel and 1 litre of concentrated nutrients from the B vessel. The circulating water takes care of the mixing and a proper measurement of EC and pH.

While adding fresh water and A and B compound and acid, a relatively large water flow is circulating water over the tank in order to get a homogenous mixture. In this line of circulating water also the EC and pH are measured to serve as the input value for the supply pumps.

When EC and pH are within the control boundaries, parallel to the mixing process water is pumped to the substrate slabs. By opening valves in the line that leaves the mixing unit each of the greenhouse compartments served by the unit are watered. In the greenhouses subject to the experiments conducted by the Chinese Academy of Agricultural Science, the mixing unit serves 4 compartments, but the capacity of the current unit is sufficient for at least 10 compartments.

The valve of a particular compartment is opened for a defined period of time (e.g. 2 minutes) and when opened a main supply line brings water to the 25 parallel sublines. The sublines run along the substrate bags and spaghetti drippers punched into the sublines bring the water to the plants that are placed on the plant holes in the substrate bags. In the experimental greenhouse, each planting row had 8 substrate bags with 4 plant holes each.
Figure 5.6 Several components of the soilless cultivation system. The spaghetti drippers are punched into the supply line. The manifold of the drippers has a relatively large resistance in order to give a uniform water distribution throughout the compartment.
The table below shows the results of the watering strategy in terms of water shots per day, the distribution of the watering over the day and the EC and pH control for the period from April 1st till May 11th.

![Table of water shots per day and EC and pH control](image)

**Figure 5.7** Irrigation turns and EC-control in April and May on a tomato crop in its productive stage.

The number of shots per day, and therefore the amount of water given, can differ a lot as the amount of radiation varies from day to day (see also chapter 6).
6 The greenhouse climate controller

A Chinese Solar Greenhouse doesn’t have many actuators to control. Stowing and deployment of the outside blanket has to be carefully monitored and is therefore a manually assisted action. Opening of the top and bottom ventilation opening is also a manual action in most of the Chinese Solar Greenhouses. Thermal screens are hardly used. Also, the application of heating systems, carbon dioxide supply and artificial illumination is rare. This means that from the 5 major systems that are controlled by standard greenhouse climate controllers as known in modern horticulture, being heating, ventilation, illumination, screening and watering, only the last one can be used in the traditional Chinese Solar Greenhouse. For the greenhouse with the AHSRS in Shouguang also the control of the pump, and in half of the greenhouse compartments the moveable screens and the dehumidification were steered by the computer.

As discussed in chapter 5, the four greenhouse compartments of the experimental facility are using a shared fertilizer mixing unit. This means that for watering the crop the greenhouse climate controller will have to switch the main water pump and one of the valves that direct the water to the 4 compartments. This way, the computer will be able to treat the compartments differently. In the first year, this was essential since the number of drippers per slab in the first compartment was only half the number of drippers per slab in the other compartments. Therefore, an irrigation turn for the first compartment had to be twice as long as an irrigation turn in the other compartments to realise an equal amount of water per plant. The watering strategy for the other three compartments in this first experimental period was equal, but in future every compartment can run on a different schedule to find out the optimal irrigation strategy.

The four compartments used by the Chinese Academy of Agricultural Science on the Shouguang Experimental site were controlled by a Hoogendoorn ISII climate computer. The computer was placed in one of the sheds of the two greenhouses.

Figure 6.1 The greenhouse climate computer.

The greenhouse climate computer (cased the red box that can be seen in the picture) is the heart of the control system. It is connected to a number of so called datapoints. Datapoints provide the input of measurements and the output to the actuators. Because of the importance of on an uninterrupted power to this computer, it gets its power from an Uninterrupted Power Supply (UPS, housed in the black casing that can be seen in the figure). The input and outputs used in the Shouguang greenhouse are shown in figure 6.2.
Sensors of the greenhouse climate controller

Figure 6.2 Measuring equipment (first line) and actuators (second line) of the greenhouse climate computer in the Shouguang Experimental greenhouse.

The aggregated results from the inner and outer climate measurements and the water temperature measurements are shown in chapter 2 through 4. The results from the measurements on water volume and EC are shown in chapter 5.

On detailed level, the climate computer facilitates the close monitoring of greenhouse air conditions for each of the compartments connected. The figure below shows an example of such a graph.

Figure 6.3 An output screen of the greenhouse climate computer.
The user interface allows for creating as many graphs as the manager of the greenhouse needs for a proper monitoring of the greenhouse conditions. The program also allows for a functional organisation of these graphs in combination with the entry tables with which the settings for the climate control actions are configured. The figure below shows an example of such an entry table.

![Graph showing climate control settings](image)

**Figure 6.4** An example of a table with which setpoints for climate control can be set.

Figure 6.4 shows how daytime and night time setpoints for heating and ventilation can be manipulated. The setpoints have a basic value, showed as the full lines, which can vary over the time of day, normally dependent on sunrise or sunset. These times are automatically computed every day, depending on the day of year, the latitude, longitude and time zone. On top of these basic values, influences can be added increasing or lowering the basic values. These influences are shown by the shaded areas.

Of course, for the Shouguang greenhouse, setting ventilation setpoints do not make any sense because there are no vents that can be opened or closed by the computer (all ventilation is performed manually). However, a heating setpoint which would switch on the AHSRS-pump when the greenhouse temperature drops below a certain threshold (e.g. 12 °C) can be entered by such a screen. This setpoint can even be influenced by, for example, the outside temperature. This makes much sense because the amount of heat in the storage system is very limited. Therefore, on cold days, the switching on of the AHSRS-pump will have to be postponed in order to save some heat for the real cold period just before sunrise.

Unfortunately the experiment started too late to experiment with this option for dynamic control of the AHSRS.

The experience showed that the operator of the Shouguang greenhouses learned to create and manage the output of the climate computer within a day and mastered the user interface within a couple of days. The local Hoogendoorn representative (施战虎, Shi Zhanhu, Tiger) showed Mrs Zhang Jinfang the way through the user interface and quite fast she could manipulate the settings for the irrigation, the screening, the dehumidification and the AHSRS-pump strategy.

In the monitoring period, starting on February 8th and running till May 11th, the climate computer has been used to control the irrigation and the on and off switching of the AHSRS-pump. The thermal screen took a long time before it was operable and controllable by the computer. When it was ready to use (March 15th), the outside temperatures were well above zero and the screen was not used anymore.

The on and off switching of the AHSRS-pump was scheduled on time only and did not use further intelligence. The irrigation however, was controlled fully dependent on the outside radiation conditions and was regularly adjusted to keep the watering in pace with the needs of the crop.
Basically, the climate computer gives a shot of water two hours after sunrise and then after every 180 J/cm² of measured solar radiation.

The needs of the crop were monitored by the grower, meaning that she adjusted the shot size such that after the second irrigation turn of the day some drainage could be observed. By ensuring a certain amount of drainage, typically 25%, the grower knows that the crop gets a sufficient amount of water.

The picture below shows the result of such a control setting.

![Cumulative solar radiation and irrigation](image)

*Figure 6.5 Cumulative solar radiation and irrigation on April 24th, 2015.*

In the morning, the climate computer starts to accumulate the amount of solar radiation measured, shown by the red line in figure 6.5. The first shot of the day is given independent on the amount of light. It is only dependent on time after sunrise. After this first shot, the computer monitors the difference between the actual accumulated radiation and the accumulated radiation at the last shot and when this exceeds the user defined threshold (here 180 J/cm²), the next irrigation shot is given. On the particular day shown in figure 6.5, this strategy resulted in a total of 16 shots and a total amount of 2800 cc per m² on that day.

The light dependent irrigation is a reliable way to adjust the irrigation to the needs of the crops as long as the drainage percentage is monitored every now and then.
The cooperative research project included a substantial contribution of Delphy. Delphy is a fast-expanding advisory and extension service that helps growers to manage their crop development. During the building of the greenhouse, but especially during the cropping season, Delphy visited the greenhouses frequently with their adviser Xizhe Hu (胡铁志). The advisory concentrated on a proper crop management, getting the fertilizer composition, EC and pH control right and in setting the irrigation strategy. The irrigation strategy aimed on getting the right balance between having the coco-peat slabs not to dry and not to wet. A special difficulty in this was that the drippers applied appeared to get blocked easily, which meant that a lot of attention had to be paid to the checking of drippers. This experience lead to the advice to replace the drippers by a better quality make before the next planting.

The tomatoes (a local variety of beef tomatoes (Shouyan 007)) were sown in the beginning of January and transplanted to the greenhouse on February 12th 2015. The plant density at the start was 2.5 plants per m², meaning 4 plants per meter slab, giving the slabs are placed in paths of 1.6 m wide. Soon after transplanting, an additional shoot was allowed on every other plant, meaning that the final plant density grew to 3.75 plants per m².

A big problem has been the fact that it took till the end of March before the greenhouse was equipped with crop support wires. This meant that the first 7 weeks, the plants were laying on the ground, growing unsupported. The grower deliberately tried to slow down the growing in the first weeks because of that. When the crop support wires were ready, the crop was carefully hung at the wires and within 5 weeks, in the last week of April, it reached the wire. There it had to be topped since the ropes had no easy system for lowering the crop.

Due to the early topping of the crop, only 8 trusses per plant were developed. The total production of this first and short growing cycle was about 5.5 kg/m². The production cannot be stated with more accuracy since the grower could not tell how many kilos were harvested without weighing.

The more detailed report on the crop management and advisory is attached as an appendix to this document.

![Figure 7.1 The tomatoes are almost ready for harvest (photo: Didi Qian, May 5th)](image)
Figure 7.2 Without an easy system for lowering the crop, the plants were topped when reaching the wire
(photo: Didi Qian)
8 Conclusions

The cooperational research project between CAAS and Wageningen UR aimed on obtaining theoretical and practical information on the working of the Active Heat Storage and Release System and on getting experience with modern greenhouse techniques on soilless cultivation and nutrition and cultivation strategies. Also the perspectives of thermal screens and dehumidification were investigated.

Unfortunately the greenhouse was finished only after winter and it took till March before the thermal screens could be operated. Moreover, the AHSRS had a lot of leakages and could not be compared with a greenhouse without AHSRS because there was no climate measurement in a nearby standard Chinese Solar Greenhouse. The thermal transparent screens were not used either since by the time the system was ready to use, the outside temperatures were not very low anymore.

The theoretical analysis of the perspective of these systems in a Chinese Solar Greenhouse however, give rise to the expectation that the improvements of these additions to the Chinese Solar Greenhouse concept is small. The Greenhouse with an Active Heat Storage and Release System shows to have an about 2 °C elevated minimum temperature in winter. The daily average temperature was hardly different. The small difference in average temperature computed was not caused by the AHSRS, but has to be attributed to the increased insulation of the northern wall. Such an increased insulation can also be applied to a standard Chinese Solar Greenhouse.

A thermal screen will also elevate the minimum temperature of the greenhouse. The increment was computed to be about 1.5 °C. Because of the increased insulation provided by the thermal screen, the outside blanket can be deployed later in the afternoon and stowed earlier in the morning. This allows for more daylight hours in the greenhouse (about two additional hours in winter). Due to the increased number of hours with the outside blanket stowed, a greenhouse with a thermal screen will provide 1% more light for plant growth in winter. However, when looking to the complete growing season the overall light entrance will be 2.5% less due to the light interception of the screen driving system and the screen package when stowed.

Dehumidification of the greenhouse by blowing in dry outside air after having it heated to the greenhouse air temperature could not be monitored in practice because of a lack of electric power. Model computations on its performance show that a system with a capacity of 3 m³ per m²/hr is likely to have a positive effect. Such a capacity will limit the greenhouse air humidity at values around 92% RH, whereas without a dehumidification system the humidity in a standard Chinese Solar Greenhouse exceeds 95% RH for about 1000 hours per year. Preventing such extremely humid conditions will help to reduce the vulnerability of the crop for diseases. The annual electricity consumption of the dehumidification system is expected to be between around 7 kWh/m² per year.

Apart from the developments in the greenhouse construction, the cooperational project aimed on improving the cultivation system. The application of coco fiber slabs as a soilless rooting medium and a fertigation system for watering and nutrition have resulted in a good quality crop. Given the fact that even after the late planting and the difficult start of the crop due to the absence of the cropping wires 5.5 kg of good quality tomatoes were harvested gives rise to the expectation that the greenhouse might produce up to 20 kg/m² per year. However, the one day power failure at the site also showed the vulnerability of the soilless cultivation system. This points out that, when using a system like this, an emergency system for watering has to be available, being either a generator to power at least the irrigation pump and preferably the mixing unit as well or a hand operated pump giving enough pressure. Probably also a buffer with irrigation water, sufficient for at least one day should be available on site.

Although the experience with the greenhouse climate controller is still very limited it can be concluded that the climate computer is well capable to manage the thermal screens, the AHSRS, the dehumidification system and the fertigation unit. All actuators are working as expected, but fine tuning will be needed to exploit the possibilities and to further improve the operation. The experiment showed that local growers became familiar with the user interface of the computer quite fast.

Finally, the two weekly visit of the Delphy adviser at the experimental greenhouse has helped the grower a lot to produce a good crop.
9 Literature

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