Greenhouse Cooling using a Rainwater Basin under the Greenhouse

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Abstract

The objective of the study was to determine the technical and economical aspects of additional applications for a rainwater basin installed under a greenhouse. The installation for cooling the greenhouse can be placed under the greenhouse. Part of the installation consists of a short-term heat store needed to lower the flow capacity of the aquifer during cooling of the greenhouse. By increasing the depth of the buffer by 13 cm, sufficient space is created to compensate for the short-term buffer. The air treatment can also be placed under the greenhouse. The option to use a cooled water layer in the basin as a heat exchanger is also investigated. The calculations are performed with computational fluid dynamics. It is concluded that the air had to be distributed with air ducts in order to obtain a good distribution. Using a water layer in the basin as a heat exchanger is less efficient and cost effective than a convectional heat exchanger. The advantage of placing the installation under the greenhouse is that the air ducts can be smaller compared to placing the installation in the corridor and ground area is saved for crop production.

INTRODUCTION

The excessive land use for greenhouses in parts of the Netherlands has led to occasional flooding in the area. After long periods of heavy rain the ditches around the greenhouses are not large enough to transport the water. For this reason rain water basins are being built. This solution is quite expensive since the area cannot be used for greenhouses. As a solution, basins are built under the greenhouses for water storage or even floating greenhouses (e.g. Aquaterranova, 2003; Bakker et al., 2005).

The high investment for constructing the basin can be made more economical by adding additional functions to this construction. Installing apparatus for climatisation under the greenhouse is investigated. The economic benefit of this is that the installation does not use surface area in or around the greenhouse.

MATERIALS AND METHODS

The water storage facility can also be used as a short-term heat storage needed for climatisation. Using an underground heat storage system (aquifer), the capacity in terms of flow rate can be reduced using short-term heat storage. Increasing the flow rate capacity of the aquifer also increases the cost of the storage. During daytime the maximum amount of cold water is needed to cool the greenhouse. The water is extracted from the aquifer and the short-term buffer, which was filled with cold water during nighttime. During the summer period the average heat load that needs to be extracted should be 300 $W\,m^{-2}$ for 10 hours, which corresponds to 10.8 $MJ\,m^{-2}\,day^{-1}$. At a temperature increase of the water of 10 °C, 260 liter of water is needed per m^2. Half of this capacity can be stored in the short-term buffer meaning an additional 13 cm has to be added to the depth of the storage. The advantage of locating the short-term buffer under the greenhouse, instead of next to the greenhouse, is that it saves costly surface area. Surface area is limited in the part of the Netherlands where most greenhouses are located making the land expensive.

Placing the installation for the climatisation beneath the greenhouse saves surface area but in addition the air can be conditioned locally, saving on energy for air distribution. Since the space under the greenhouse is primarily build for water storage during excessive rainfall, some restrictions have to be considered. (1) The available space has to be sufficient to store the water during severe rainfall and (2) the rainwater must not come into contact with the buffer water in order to prevent contamination.

Heat Transfer

Solar radiation entering the greenhouse is transferred into sensible heat and latent heat as the crop transpires. The transpiration depends on the relative humidity, CO_2 concentration, leaf area index, air temperature and the solar radiation in the greenhouse (Stanghellini, 1987). In Fig. 1 the percentage of transpiration related to the solar radiation is depicted at a relative humidity of 80%, a CO_2 concentration of 1000 ppm and a LAI of 3.

When humid warm air passes a cold surface heat and mass are transferred. The heat transfer depends on the temperature difference and the mass transfer on the concentration difference. The heat α and mass k transfer coefficient are correlated as by the Lewis equation:

$$\frac{\alpha}{k} = \left(\frac{\rho}{c_p}\right)^{1/3} \left(\frac{\lambda}{\delta}\right)^{2/3} \tag{1}$$

where ρ is the density of the air in kg m^{-3}, c_p the specific heat of air in J kg^{-1} K^{-1}, λ heat conduction of air in W m^{-1} K^{-1} and δ the diffusion coefficient in m^2 s^{-1}.

The total heat transfer (latent and sensible) to a cold surface is dependent on the relative humidity of the air passing. In Fig. 2 the total heat transfer is depicted as a function of the air temperature and relative humidity. The cold surface has a temperature of 10°C and the heat transfer coefficient is 10 W m^{-2} K^{-1}. The heat transfer is larger when the relative humidity is high. Especially in periods with high solar radiation the heat transfer has to be high in order to cool the greenhouse sufficiently. Additional evaporation by means of for example sprinklers, is needed in this case since the crop transpiration is not sufficient as can be derived from Fig. 1.

Design Process

Based on the theory a design where the climatisation of the greenhouse is placed under the greenhouse is made (Fig. 3). The air is forced to move over a layer of cold water under the greenhouse. The air transfers heat and moisture to the water provided the water is cold enough. Using a sprinkler, the air is moisturized before flowing back into the greenhouse. This design was evaluated using CFD with the following conditions: outside temperature 25°C, heat transfer coefficient at the cover 10 W m^{-2} K^{-1}. The long wave radiation exchange between the roof and sky is included assuming a sky temperature of 5°C. The height of the greenhouse is 4 m and the length of a section is 20 m. The crop forms a resistance to the air and has a height of 3 m, the lowest meter of the crop is de-leafed as commercial practice in dutch tomato growing. The solar radiation coming into the greenhouse is 700 W m^{-2} of which 200 W m^{-2} is used for crop transpiration. The crop transfers the energy to the greenhouse air. The air duct below the floor of the greenhouse is 50 cm in height and the water temperature is 10°C with a saturated vapour concentration of 7.6 g kg^{-1}.

RESULTS AND DISCUSSION

The CFD calculations of the design (Fig. 3) are depicted in Fig. 4. The temperature is extremely high in the greenhouse. The crop transpiration is less than the moisture extracted by the system causing a low relative humidity. The cold air coming from beneath the greenhouse tends to remain near the greenhouse floor not mixing with the warm air near the crop. The situation is improved by placing a barrier with a height of

1 meter in the centre of the greenhouse and using evaporative cooling as can be seen in 0A persistent problem is the unacceptable temperature gradient of more than 5°C. The heat transfer in the design is sufficient to remove the solar radiation energy provided the water is cold enough (< 10°C) and the heat transfer coefficient is large enough meaning the air velocity over the water surface has to be high (> 1 m s^{-1}).

The temperature gradient can only be resolved using an air distribution system similar to the GeslotenKas (Ecofys, 2003). The air conditioning can still be placed under the floor of the greenhouse and it can be made of shorter ducts, which saves energy and space. Using a water layer as a heat exchanger is possible though costly since an additional floor has to be constructed beneath the greenhouse. The costs have to be compared to a conventional heat exchanger.

CONCLUSIONS

Technically the space under the greenhouse can be used as a short-term heat buffer. The installation for the climatisation can also be placed under the greenhouse saving costly ground area. The latent and sensible heat transfer has to be sufficient to remove all the solar radiation coming into the greenhouse which results in constraints regarding the contact area between water and air and the temperature of the water. Conditioned air has to be distributed locally, meaning the distance between injection points has to be less than 1 meter, to avoid temperature and humidity gradients.

The economic feasibility largely depends on the cost of the ground in the area where the greenhouse is located. The contribution to underground water storage has to be substantial. The cost of building an underground water store of 2.5 m are estimated to be 200 €/m² (Ham, 2003). Including a short-term heat store will cost around 20 €/m² extra. Only a grower with a major shortage of space will accept these costs. Placing the installation underground instead of in the greenhouse saves approximately 5% surface area, so offers 5% more production. The costs of placing the installation under the greenhouse are around 10 €/m² so depending on the crop this can be economically positive.

ACKNOWLEDGEMENTS

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Literature Cited

Aquaterranova 2003. Haalbaarheidsstudie Kelders onder Kassen. www.aquaterranova.nl

Bakker, J.C., de Boer, S.B., Meijer, J.P.R., Leppers, R.F.R., de Ruiter, M.J. and Zevenbergen, C. 2005. Floating greenhouses: an expert system for integral design. Acta Hort., 691: 541-548.

Campen, J.B. and Zwart, H.F.de. 2004. Multifunctioneel gebruik van een tuinbouwkas met kelder. A&F 272, Wageningen, The Netherlands.

Ecofys, 2003. Telen in een gesloten tuinbouwkas; praktijkexperiment. E48031, www.tuinbouw.nl

Stanghellini, C. 1987. Transpiration of greenhouse crops. PhD thesis, Wageningen University.

Ham, J.H.M.van. 2003. Voorstel Waterblock 07-03-03. www.waterblock.nl The Netherlands.

Zwart, H.F.de. 2004. Praktijkexperiment Duurzame energieverzameling door middel van daksproeiers. A&F Rapport.

Figures

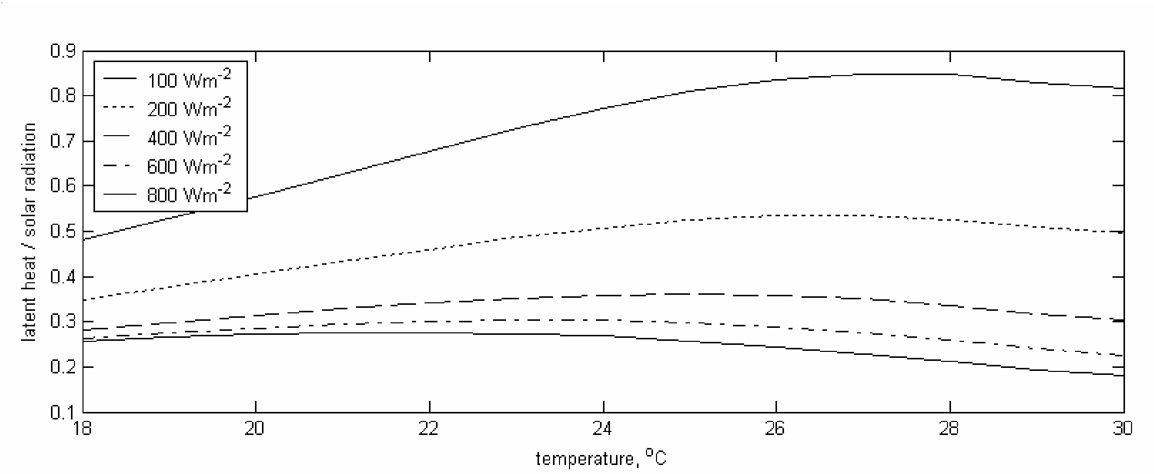

Fig. 1. The ratio of latent heat to the outside solar radiation as a function of greenhouse temperature at a relative humidity of 80%, CO_2 concentration of 1000 ppm and a LAI value of 3.

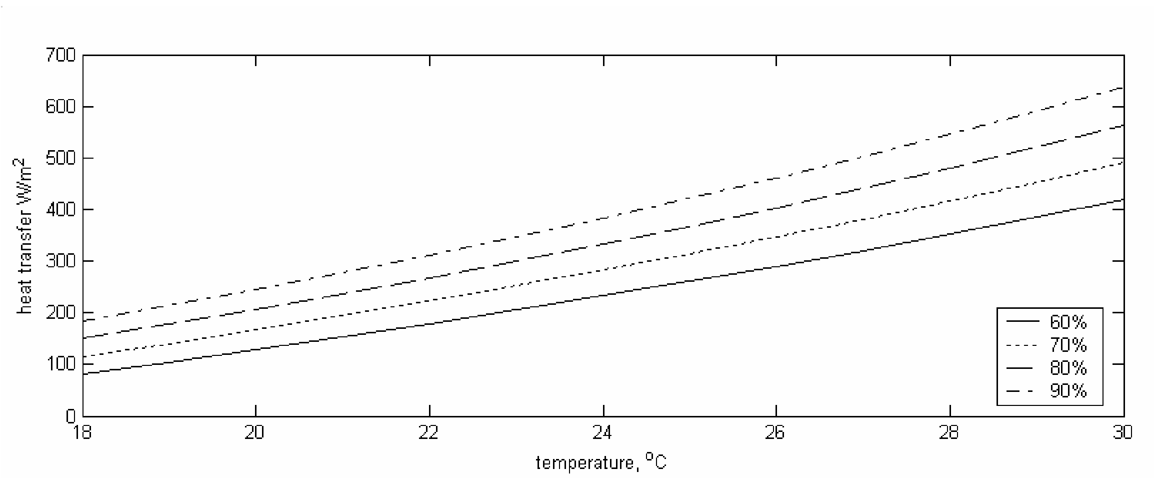

Fig. 2. The heat transfer (latent and sensible) to a cold surface (10°C) as a function of air temperature and relative humidity when the heat transfer coefficient is 10 W m^{-2} K^{-1}

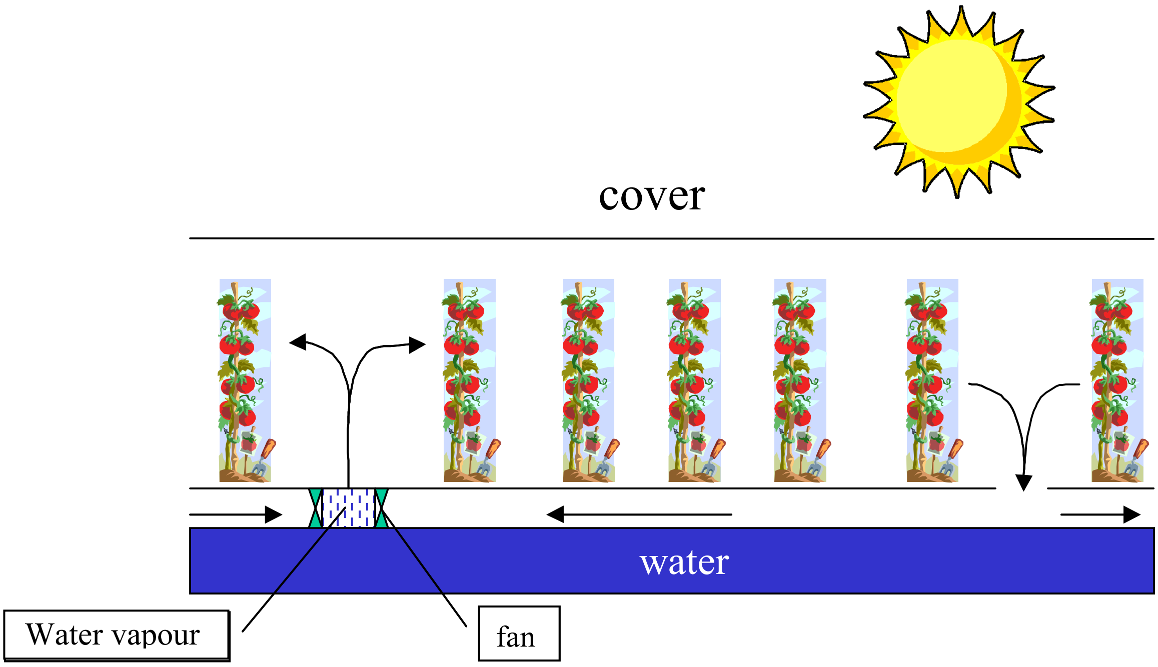

Fig. 3. Design of the closed greenhouse with underground climatisation using a cold water layer.

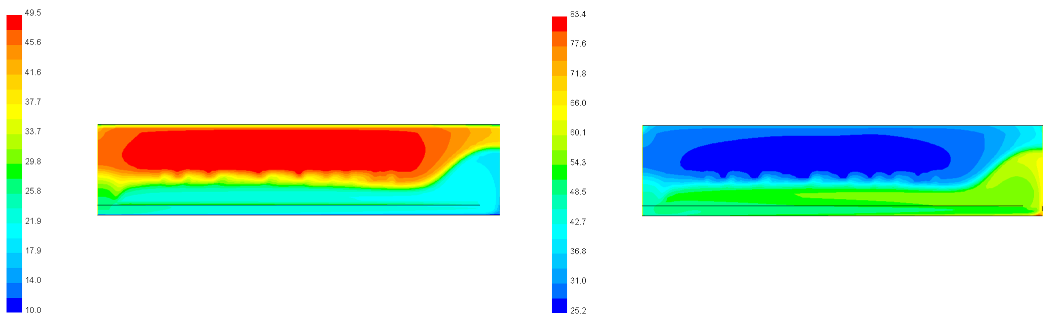

Fig. 4. Temperature (left) and relative humidity (right) in the greenhouse where the air is cooled at a water layer of 10°C below the greenhouse. In the greenhouse the air flows for right to left.

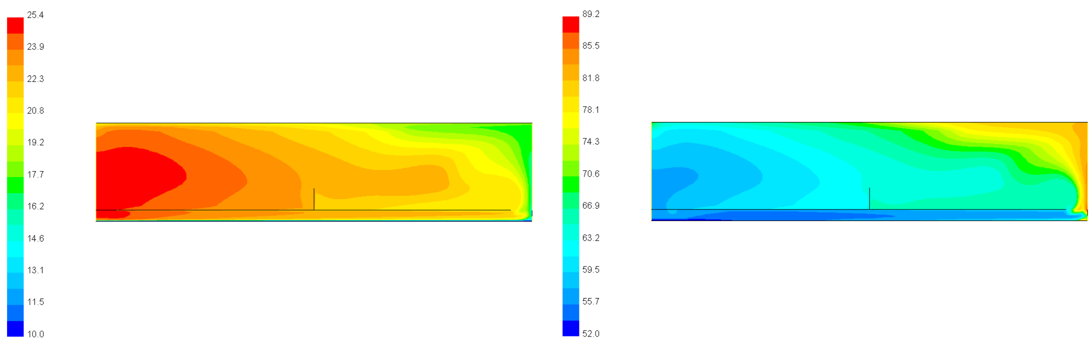

Fig. 5. Temperature (left) and relative humidity (right) in the greenhouse where the air is cooled at a water layer of 10°C below the greenhouse. In the greenhouse the air flows for right to left. A wall of 1 meter is placed in the centre and evaporation is increased.