Evaluation of Roof Spraying as a Low Cost System for Sustainable Energy Collection

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Abstract

In case a greenhouse is heated by means of a heat pump, fossil fuel consumption of greenhouses can be diminished. In nowadays research and development projects around heat pumps in horticulture, the evaporator is fed by a storage system that stores thermal energy in aquifers at depths of some 50 m. However, such a storage system must be charged. Recently, a number of charging methods are studied. At the one side of the options, projects can be mentioned that focus on regenerating the storage system while cooling the greenhouse to such an extent that it can be kept (almost) closed. In those cases the heat collection is at least triple the amount of heat that is needed for charging the storage facility. At the other side of the range of options, as in this paper, research is focussed on collecting only the amount of heat required to compensate for the low temperature heat demand of a suitably sized heat pump. This paper shows that a sprinkling system, as a modification on already existing systems, potentially collects more than 500 MJ per m² per year, which gives the opportunity to save this amount of fossil fuel (about 16 m³ of natural gas per m² per year)

INTRODUCTION

Dutch horticulture aims to increase the contribution of sustainable energy in greenhouse heating. A promising contribution to this goal is the application of summer surplus heat for heating in winter. In terms of energy, the heat surplus exceeds the total demand for heating. However, since surplus heat in a greenhouse in summer occur as greenhouse air that has to be cooled at temperature levels around 25 °C it is hard to gather, store and apply this energy in an economic way.

Currently, a number of research projects are carried out to meet this challenge. In one experiment, the objective is to install such a cooling capacity that all heat excesses can be removed. This system is based on heat exchange in a cross-flow heat exchanger by means of forced ventilation. Together with the dehumidification at the heat exchanger this installation allows to keep the greenhouse completely closed. More details and results of this full scale experiment are presented on www.innogrow.nl/en/. Other experiments do not aim at a complete closure of the greenhouse, but only diminish the ventilation rates to some extent. The third approach, and subject to the present study, concentrates on gathering a significant amount of sustainable energy at relatively low costs, without bothering too much about the cooling capacity. After having discussed a number of ways that have been studied in the past years, this paper will focus on the perspectives of a roof spraying system. These sprinkling systems can already be found on many greenhouses (although not meant to collect sustainable energy), or can be mounted for € 1 to 2 per m² greenhouse. By cooling the water that comes back from the drainpipes of the greenhouse before it is sprayed again, heat is extracted and solar energy is being collected. A schematic graph of this system is depicted in Figure 1.

In all variants where summertime surplus heat is gathered from the greenhouse air or its envelope, cold water of some 8 °C is warmed to temperature levels around 20 °C. The energy present in this water can be exchanged with water in aquifers. In the Netherlands, at most places, these can be found at depths around 50 m. By exchanging heat to water and sand in aquifers, the summertime solar heat surpluses can be stored to
be used in winter by means of a heat pump. During operation, by cooling water coming from the warm side of the storage doublet to some 6 °C, the heat pump extracts energy. The heat pump transfers this energy to temperature levels around 45 °C that can be used for greenhouse heating. The cold water is brought back into the aquifer by means of the cold well of the doublet. Thus, during winter a stock of cold water is created. A characteristic situation during the operation of such a heat pump is depicted in Figure 2.

For a sustainable way of operating the concept, the yearly heat supply to the storage system in summer must balance the heat extraction in winter. This means that besides the heat collection, a lot can be said about the heat extraction (c.q. production of cold water) in winter. However, this paper limits its scope to the collection of heat and discusses the wintertime low thermal heat application only briefly.

HEAT COLLECTION IN SUMMER

In 2001 and 2002 several ways of using a greenhouse as a solar heat collector have been studied (Campen et al., 2001; de Zwart and Swinkels, 2002). Contrary to hot water solar heat collectors as known from an increasing number of homes and buildings, the heat collection process in a greenhouse will yield energy at low temperatures. After all, in greenhouses temperatures that exceed 25 to 30 °C are commonly unfavourable, which means that some 25 °C must be considered as the absolute maximum temperature at which heat surpluses can be withdrawn from the greenhouse. In practice, however, quite lower temperatures will be reached, as the consequence of a trade off between the size of the heat exchanging surface and the temperature lift during the heat collection process.

In the studies mentioned above theoretical computations and experiments have been carried out to determine the potentials of a dual use of the existing heating pipes, the potentials of special finned pipes and the perspectives of a roof spraying system. Dual use of heating pipes takes advantage of the fact that during periods with a heat excess, the heating pipe circuitry can be fed with cold water in order to withdraw heat from the greenhouse. The study was limited to systems based on free convection in order to avoid large electricity consumption levels. Besides theoretical computations by means of an extensive greenhouse simulation model, a number of configurations have been tested in a 200 m² greenhouse in the summer of 2001. The practical results matched very well with the results of a simulation model.

All pipe-systems in the greenhouse resulted in poor heat collection potentials in comparison to the level of investments. An ordinary dual used heating system with a heat exchanging surface of 0.2 m² per m² greenhouse (common for a great fraction of Dutch greenhouses) was calculated to yield some 150 MJ/m² per year at a temperature level of 17 °C. Investing about € 7 per m² for doubling the number of pipes increases the heat extraction potential to 240 MJ/m². Other, specially designed systems like longitudinally or perpendicularly finned pipes, yielded amounts of energy around 90 to 180 MJ/m² per year.

The poor results were caused by the small size of the existing heat exchanging surfaces and the large disadvantages of additional surfaces (like high costs or diminished radiation levels for crop growth).

These problems do not occur when using the roof of the greenhouse as a heat exchanger. Providing that it’s flat and rigid and single layer, as is the case with over 90% of the Dutch greenhouse area, spraying the surface with cold water gives a large heat exchanging surface. The cold water, while warming up, runs down the roof into the gutter and can be carried off through the drainpipes to a centralized heat-exchanging unit. The next paragraph discusses the roof spraying system in more detail.

ROOF SPRAYING WITH COLD WATER

By spraying the roof of a greenhouse with cold water, a large cold surface is created. Thus, heat exchange from the inside greenhouse air and the outside ambient air to the greenhouse envelope will be enhanced. The heat exchange rate depends primarily on the temperature difference between the surface and the ambient air (the temperature at the
top side of the roof is considered to be the same as the temperature at the bottom side since a heat exchange coefficient of 200 W/(m² K) between upper and lower side will almost equalize both temperatures). On both sides of the roof, the heat exchange is governed by sensible and latent heat exchange. On the inner side of the roof mostly there will be condensation because of the high humidity of the greenhouse air. At the outer side, the roof is wetted by the spraying system and evaporation depends fully on the dewpoint temperature of the outside air. When the outside air is not too dry and the mean temperature of the water sprayed is low, it is even possible that vapour from the outside air condenses at the outer roof surface. However, since a high temperature lift between the cold water and the water returning from the drainpipes is desirable for storage purposes, quite often there will be some evaporation of the water sprayed. A sketch of the heat and mass fluxes involved is depicted in Figure 3.

All fluxes mentioned in Figure 3, except for the cooling power and the latent heat associated with the evaporation from the outer side of the cover are commonly distinguished in a dynamic greenhouse climate simulation model (e.g. Bot, 1983; de Zwart, 1996). Thus, the effect of roof spraying can be integrated into a model simply by adding a module computing the energy fluxes associated with warming and evaporation and a device controlling the simulated spraying system. Such a module can be based on the same formulas used to compute evaporation or condensation to the inner side of the roof (see Bot, 1983; de Zwart, 1996). By stating that the sprayed water reaches the gutter with a temperature equal to the mean temperature of the greenhouse cover, the cooling power can be computed by the product of temperature difference, spraying flow and volumetric heat of water.

RESULTS OF MEASUREMENTS COMPARED TO SIMULATIONS

At the end of summer 2003 and in spring 2004, experiments with a cold water roof spraying system have been carried out at 3000 m² of a greenhouse of 18000 m². In the greenhouse, ornamental pot plants were grown (Bromelia) under warm and humid climate conditions. The greenhouse was already equipped with a customary roof spraying system with a spraying rate of 1.8 litres per m² per hour (achieved by one sprinkler per 50 m²). The on/off control signal was generated by the climate controller of the greenhouse. When switched on, the sprinklers on the 3000 m² part, were fed with water cooled to 8 to 10 °C by a chiller. The temperature of the cold water, the temperature of the water coming down the drainpipes and the flow of the drainpipes from this part of the greenhouse was measured, so that the amount of energy accumulated at the roof could be computed. Note that the usage of the chiller was only necessary because of the experimental character of the measurements. In the final design, cooling power comes from the cold well of the aquifer doublet (see Fig. 1).

In total, the roof spraying system was switched on for 380 hours, from which 295 hours were suitable for analysis. These running hours were achieved on 53 days. Based on the theory discussed around Figure 3, the greenhouse climate simulation model KASPRO (de Zwart, 1996) was extended in order to simulate the physics of a cold water roof spraying system. A comparison of the simulated and measured heat collection was made by computing the temperature at which water runs down the drainpipes, followed by the calculation of temperature lift and multiplication with flow and volumetric heat. This simulation was made while forcing the measured spraying flow and temperature to the simulation model (in normally running mode, the spray rate controller of the model decides itself at what time the spraying system is switched on and off and computes the required cold water temperature). In Figure 4 the measured and simulated daily amount of energy collected by the roof spraying system is depicted. The figure shows that the model fairly well describes the amount of energy that can be collected from the greenhouse cover. The total amount of heat collected from the roof in these 53 days was measured to be 23 MJ/m². The simulation model computed 22 MJ/m². Also the diurnal patterns of simulated and measured temperature of the water coming down the drainpipes (not shown in this paper) showed a very good resemblance.
Since the simulation is based on deterministic physical relations, the model is suitable to run scenario studies to investigate the potential of gathering sustainable energy in other situations. Currently, among tomato growers in the Netherlands, there is high interest in the possibilities of roof spraying systems. Therefore, in the next section the perspectives for a roof spraying as a way of collecting sustainable energy at tomato nurseries are discussed. An important fact with respect to the design of a roof spraying system is the maximal flow rate of the sprinklers. Therefore, the computations are made for three spraying flow rates.

COLLECTION OF SUSTAINABLE ENERGY BY A ROOF SPRAYING SYSTEM IN A TOMATO GREENHOUSE

In comparison to the climatic demands of a bromelia canopy, tomato is grown at lower temperatures, which means that more often the greenhouse air temperature exceeds the temperature at which vents are opened. Every time the vents are opened on temperature excess, the greenhouse has a heat surplus, and gathering of surpluses by means of a roof spraying system contributes to harvesting of sustainable energy. However, when outside temperature is low (e.g. on bright winter days), the greenhouse cover temperature may be quite cold, which seriously limits the energy collection by the spraying system. Therefore, roof spraying is prohibited in case the cover temperature is lower than 13 °C.

For a mean Dutch year, the cooling demand of a tomato crop, combined with the restriction of 13 °C as a minimum temperature, yields about 2700 h potential running time. The amount of energy that can be gathered during these hours depends on the maximum flow of the spraying system. This can be seen in Table 1. The table shows that the yearly collection of heat excesses goes up from 235 MJ/m² a year to 560 MJ/m² when the maximum flow rate grows from 2 litres per m² per hour to 6 litres per m² per hour. The increment of the amount of energy gathered is not linear. This is a result of setting a minimum temperature for the water that comes down the drainpipes. Setting such a minimum temperature limits the minimal mean temperature at the greenhouse cover. As a consequence, during periods when greenhouse air temperatures are not too high, the heat collection process is limited by the heat fluxes to the cover and not by the cooling capacity of the spraying system. In those cases the spraying system flow rate controller decreases the spraying rate. It is also due to this that the total amount of water sprayed at the roof does not grow linear with the maximum flow rate.

Table 1 shows clearly that higher maximum flow rates yield a relative lower volumetric mean temperature of the water coming down the drainpipe. This drops from 18.9 °C for the lowest spraying capacity to 16.8 °C for the case where the maximum spraying capacity is 6 litres per m² per hour.

The amount of heat collected by the spraying system, and stored in the aquifer, enables a heat pump to contribute to the greenhouse heating by means of sustainable energy. Thus, stating that heating a greenhouse growing tomato’s in the Netherlands uses about 1400 MJ a year, a cold water roof spraying system with a flow rate of 2 litres per m² per hour, in conjunction with a suitable heat pump, enables a 17% sustainable energy contribution to the heat demand. With a flow rate of 4 litres per m² per hour, 30% of the heat demand can be achieved by sustainable energy and with a flow rate of 6 litres per m² per hour the potential contribution grows to 40%.

CONCLUSIONS

Experiments with the use of sprinkling systems as a means to collect energy from the greenhouse cover during periods with a heat surplus showed promising results. Based on these experiments the greenhouse climate simulation model KASPRO was extended with a module that describes the physics of a roof spraying system and a module that controls its flow rate and temperature. The comparison of the results of the model with the measurements showed satisfactory results.
With the extended model, a scenario analysis was made to compute the perspectives of a cold water roof spraying system in a greenhouse growing tomatoes in the Netherlands. It was shown that the amount of heat that can be collected can easily reach up to 30 or 40% of the annual heat demand of such a greenhouse. This means that, by using a suitable heat pump, roof spraying with customary and relatively cheap sprinklers, around one third of the energy consumption related to heating of greenhouses growing tomatoes can be of sustainable origin.

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Literature Cited


Tables

Table 1. A number of performance indicators of a roof spraying system designed to collect sustainable energy from surplus heat in a greenhouse growing tomato’s at mean Dutch weather conditions for three maximum flow rates.

<table>
<thead>
<tr>
<th></th>
<th>2 litres/(m² hr)</th>
<th>4 litres/(m² hr)</th>
<th>6 litres/(m² hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat collection [MJ/(m² yr)]</td>
<td>235</td>
<td>420</td>
<td>560</td>
</tr>
<tr>
<td>total water sprayed [m³/(m² yr)]</td>
<td>5.5</td>
<td>10.6</td>
<td>15.4</td>
</tr>
<tr>
<td>mean drainpipe temp [°C]</td>
<td>18.9</td>
<td>17.7</td>
<td>16.8</td>
</tr>
</tbody>
</table>
Fig. 1. A roof spraying system gathering solar heat excesses by spraying cold water at the greenhouse and storing heat from the warmed water that comes down the drain-pipes.

Fig. 2. Typical situation when heating a greenhouse with a combustion engine powered compression heat pump.
Fig. 3. Heat fluxes when using a cold water roof spraying system.

Fig. 4. Measured and simulated daily amount of heat gathered by the roof spraying system on 53 days (sorted on magnitude).