Greenhouse Cooling and Heat Recovery using Fine Wire Heat Exchangers in a Closed Pot Plant Greenhouse: Design of an Energy Producing Greenhouse

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Abstract

A greenhouse cooling system with heat storage for completely closed greenhouses has been designed, based on the use of a fine wire heat exchanger. The performance of the fine wire heat exchangers was tested under laboratory conditions and in a small greenhouse compartment. The effects of the system on the environmental conditions (temperature and humidity distribution) in the greenhouse were simulated to decide on the final lay out of the system. Finally the system was implemented on a large scale in a pot plant greenhouse complex of 2500 m^2. The system is being tested under practical conditions and compared to a traditional heating and ventilation system in a comparable reference compartment of 2500 m^2. This paper describes the set up of the greenhouse system, the first simulation results achieved with the system with respect to environmental conditions and energy use.

INTRODUCTION

The Dutch horticultural industry aims at the introduction of “fossil fuel free” greenhouses in 2020. In the attempt to reach this target a large programme has been started under the name” Greenhouse as energy source”. For decades it has been recognized that greenhouses are large solar collectors which collect almost 80% of all incoming solar radiation (e.g. Garzoli and Shell, 1984). For north west European conditions this equals on a yearly basis up to 2800-3000 MJ m^{-2} while the average energy use (in the form of fossil fuel) under the same conditions, is about 40-50 m^3 natural gas per m^2. At 31 MJ m^{-3} this equals up to 1500 MJ m^{-2}. Since the incoming solar radiation represents about twice the energy used in the greenhouse itself, this theoretically creates the possibility to use the greenhouse as a combined crop and heat producing system.

In traditional greenhouses the surplus of incoming solar radiation is removed from the greenhouse by ventilation. Thus, to maximize the effect of the greenhouse as a solar collector, the major challenge is to keep the vents closed and efficiently extract the heat from the greenhouse, store it in a heat storage and re-use it during periods with heat demand. The first steps in this road were already set in the early 1980s when several projects were carried out to extract heat from the greenhouse and store it for reuse (e.g. Blackwell and Garzoli, 1981). A decade later this was followed by research on forced ventilated / semi-closed greenhouses: Bakker, (1992a, 1992b) and after additional experiments in the late 1990s and 2000-2002 (Schoonderbeek et al., 2003) this led to the introduction of the “Closed Greenhouse”. This greenhouse set up comprises long term heat storage in aquifers, heat exchangers and air distribution system, which were combined into a complete production system (Opdam et al., 2005).

The project described here is one of the key projects within the program and focuses on the design and optimization of a completely air conditioned greenhouse with the ultimate goal to minimize the amount of fossil energy used and to produce both horticultural products and more energy (in the form of warm water) than the fossil energy input (both expressed as MJ m^{-2}). The basis behind the concept is the combination of a highly insulated greenhouse, long term heat storage (summer to winter) in aquifers and a distributed system of efficient fine wire heat exchangers. This has the advantage of circulating cold water as a major transport medium for cooling instead of large quantities of cold air commonly used in cooling systems for greenhouses.

MATERIALS AND METHODS

Greenhouse Concept and Heat Exchangers

The basic concept of the energy (heat) producing greenhouse is represented in Fig. 1 (for simplicity the heat storage system has been left out). To maximize the energy output, the system requires the combination of: maximum transmission of solar radiation, minimal heat loss from the greenhouse and an efficient air conditioning system. With the availability of the recently developed Lexan® ZigZag™ greenhouse covering material (Sonneveld and Swinkels, 2005), the first two requirements could be met. For the efficient air conditioning system a recently developed fine wire heat exchanger, with a very high heat transfer coefficient compared to its pressure drop is used. The heat exchanger is a development of the commercial companies FiWiHex and HSH. The major component of the FiWiHEx heat exchanger consists of 15 cm long copper capillaries (internal diameter 1 mm) combined with 1500 woven fine tin coated copper wires (0.1 mm diameter). A heat exchanger has two blocks each with 113 x 15 x 15 cm woven copper wire with a total area of 5.1 m^2 (Fig. 2).

It behaves somewhere between a cross-flow and a counter-flow heat exchanger and to examine the performance a numerical matrix based model (Figure 3) was set up for air and water temperature to calculate the heat flux in both directions and the heat transfer from water to air based on the heat capacity of the air and water flow. To describe the condensation process also the absolute humidity matrix is calculated with a temperature of the surface equal to the water temperature at this specific location. The theoretical model was validated using measurements in a climate chamber for a wide range of environmental conditions (air temperatures from 15 to 30 ^{o}C), a range of water temperatures (10 to 25 ^{o}C), water flow (1 to 10 liter/min) and air flow (150 – 1000 m^3 h^{-1}) through the heat exchanger.

Simulation and Measurement of Air Temperature Distribution

1. Simulation. The matrix model of the heat exchangers was combined with a CFD model for air flow and temperature distribution to calculate both the temperature distribution and the year round performance and energy consumption. For these simulations the following boundary conditions were used (based on the requirements of the tropical pot plants to be cultivated in the greenhouse): a minimum greenhouse temperature of 17 °C , a maximum temperature of 25 °C and a maximum humidity level of 90%.

Below the minimum level the heat exchangers are used for heating, above the maximum level for cooling and if the relative humidity exceeds 90% also for dehumidification.

The greenhouse cover is a Lexan® ZigZag™ high insulating material (Sonneveld and Swinkels, 2005) with an U value of 3.4 $Wm^{-2}K^{-1}$. The span width of the greenhouse is 12.80 m, the column height is 5 m and the distance between columns in the direction of the gutter is 4.5 m. For the simulations the greenhouse geometry was considered a repeatable greenhouse section of 6.40 x 4.5 meters (half a wide span of 12.80 m by the distance between the columns). In the greenhouse movable benches will be installed with a water layer on top for irrigation.

The heat exchangers are to be placed under the gutter creating an upwards air stream towards the gutter and recirculation underneath the movable benches.

Based on the measured and simulated performance of the heat exchangers, the optimal lay-out of the distribution of heat exchangers in the greenhouse was investigated by Computational Fluid Dynamics (CFD). CFD is a widely used tool to determine the flow field and temperature distributions in and around geometries. A general description of CFD is given by Mistriotis et al. (1997) and it is frequently used for optimizing the design of ventilation systems in greenhouses (e.g. Campen, 2003). In the CFD program, a system is modelled by discretising space and time (finite volume method) and by solving the conservation equations for the discretised parts for the relevant quantities considered. The conservation equation reads:

$$\frac{\partial \vec{\varphi}}{\partial t} + \vec{\nabla} \cdot \vec{\varphi} \vec{v} = \vec{\nabla} \cdot \left(\Gamma_{\varphi} \vec{\nabla} \vec{\varphi} \right) + S_{\varphi}$$

where v is the velocity vector in m s^{-1}, Γ_{φ} the diffusion coefficient in m^2 s^{-1} and S_{φ} the source term. The symbol φ represents the concentration of the quantity considered. Solving this provides transport between the parts of the model, thus the flow fields for heat and mass can be determined.

2. Measurements. To validate the simulations of the temperature differences, a small compartment was used on a commercial potplant nursery. Using polyethylene film a compartment was separated form the rest of the greenhouse and three FiWiHex heat exchangers were installed and large *Ficus Benjamina* potplants were placed on the benches to create evaporation and the normal crop resistance for air circulation as to be expected in the full scale greenhouse. Temperature and humidity measurements were done in August and September 2005 using aspirated dry/wet bulb PT-100 elements.

RESULTS AND DISCUSSION

The results of the validated simulation model of the heat exchanger are presented in figure 4. The heat transfer coefficient reached 600 W K^{-1} and the maximum cooling capacity at a temperature difference T_{air}-T_{water} of 20 ^{o}C was about 20 kW per heat exchanger. In the Netherlands the peak load of solar radiation in greenhouses is about 800 W m^{-2} (based on a maximum of 1000 W m^{-2} and an average overall greenhouse transmission of 80%). To cool the greenhouse at a maximum temperature of 27 ^{o}C requires a water temperature of 7 ^{o}C (at delta T of 20 ^{o}C for the heat exchanger) and the installation of one heat exchanger per 25 m^2 greenhouse. In addition to cooling, the low water temperature is also required for controlled dehumification, e.g at the required minimum temperature of 17 ^{o}C and a relative humidity of 90%, the dewpoint temperature is 15.3 ^{o}C. In practice this means that the outflow water temperature should be below this dewpoint. This can only be achieved at much lower inflow temperatures than 15 ^{o}C and/or very high waterflow through the heat exchanger, at lower temperatures the amount of energy for recirculation pumps and installation costs will be significantly reduced. Based on a range of inflow temperatures from 7 to 12 ^{o}C it was concluded that 8 ^{o}C inflow temperature will be the best in practice (Campen en de Zwart, 2005).

Figure 5 shows CFD simulation results of the temperature distribution in a vertical plane inside the greenhouse during heating at an outside temperature of -15 ^{o}C and a heating temperature of 17 ^{o}C with and without 10 cm gaps between the movable benches. With gaps between the benches, not only the horizontal temperature variability increases but also the efficiency of the heat exchangers decreases because of the reduction of temperature difference between incoming and outgoing air. To reach the same heat transfer more air has to be circulated, thus increasing the electrical power for the fans. So to prevent large temperature differences and to reduce the input of electrical power the benches have to form a completely closed surface.

The cooling situation was simulated only for the situation without gaps between the benches. At an average temperature in the greenhouse of 25 ^{o}C, the temperature gradient over the growing benches reached up to 3 ^{o}C, however for the majority of the growing area, the temperature differences are within 1 ^{o}C (Fig. 6). This is considered as an acceptable difference since for Dutch conditions, cooling at maximum capacity, will be restricted to less than 100 hours per year. The actual measured temperature and humidity differences during the cooling modus were small (less than 2 °C) Measurements at night with heating showed even smaller differences (about 1 °C). These results are within the range as expected from the CFD simulations, so based on the combined results of simulation and measurements it was concluded that using the FiWiHex heat exchangers in this configuration and with the benches close together will lead to acceptable environmental growing conditions under (Dutch) winter, as well as under summer conditions.

Simulation of Energy Performance and Overall Output

Using the above information, the final design of the installation was made and additionally the year round energy performance and expected overall heat output was simulated using the KASPRO greenhouse climate and energy model (de Zwart, 1996). The original model describes the amount of energy entering the greenhouse (from solar radiation, primary and secondary heating circuits and the CO_2 heating system), the amount of energy used to maintain air temperature, and energy losses through the roof, walls and ground surface. For this project the model was expanded with the FiWiHex heat exchanger model, a cooling tower, heat pump and a long term heat storage (aquifer).

As stated before the major challenge is to keep the vents closed during the summer and efficiently extract the heat from the greenhouse, which requires a substantial amount of cold water at a temperature level of 8 °C. This can be achieved in different ways, e.g. using a cooling tower or a heatpump/ mechanical cooler. Using a cooling tower will create loss of potentially useable heat and this is considered undesirable. However also for some practical reasons a heat pump is preferred:

1. Even if all cooling water is stored with a temperature of 25 °C, only some 40% of the water can be extracted at that temperature, the rest will be extracted at a lower temperature because of a gradually decreasing temperature due to dispersion of heat towards the environment. Therefore a heat pump is required to increase the temperature level for heating during the second part of winter.
2. To realise a thermal balance in the aquifer requires that the cold well has a temperature below the natural ground water temperature (in the Netherlands about 12 °C) which can only be achieved using a heat pump.

Using the modified simulation model the energy use and heat output of different designs with the FiWiHex heat exchangers were calculated (de Zwart and Campen, 2005). Based on these simulations the following decisions were made for the major components of the final lay-out (Figure 7) of the system to be experimentally tested:

- A heat pump to avoid energy loss during dehumidification and maintain the temperature in the warm well.
- Heat delivery to other parts of the same greenhouse at a temperature level of 40 °C.
- Co-generation of heat and power to drive the electric components and to obtain CO_2 for CO_2 supply to the greenhouse.
- Using the heat pump to generate water of 8 °C for cooling/ dehumidification.
- Using a water/water heat exchanger between the aquifer and FiWiHex water circuit to prevent corrosion and contamination.

CONCLUSIONS

Taking into account all boundary conditions (energy efficiency, practical applicability, CO_2 availability and maximum heat output) has led to the following concept: a co-generator for heat, CO_2 and power production, an electrical heat pump, heat delivery to additional greenhouses at 40 °C and a cooling water temperature of 8 °C. With this system a year round heat production of about 800 MJ can be expected, which is equivalent of 25 m^3 natural gas (de Zwart and Campen, 2005). The experimental greenhouse will be completed in April 2006 and its actual energy performance and the crop responses will be investigated in a two year experiment.

ACKNOWLEDGEMENTS

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Figures

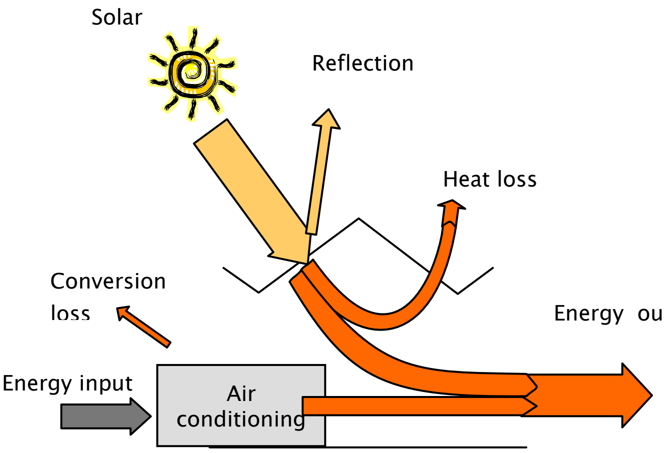

Fig. 1. Energy flows in the energy (heat) producing greenhouse.

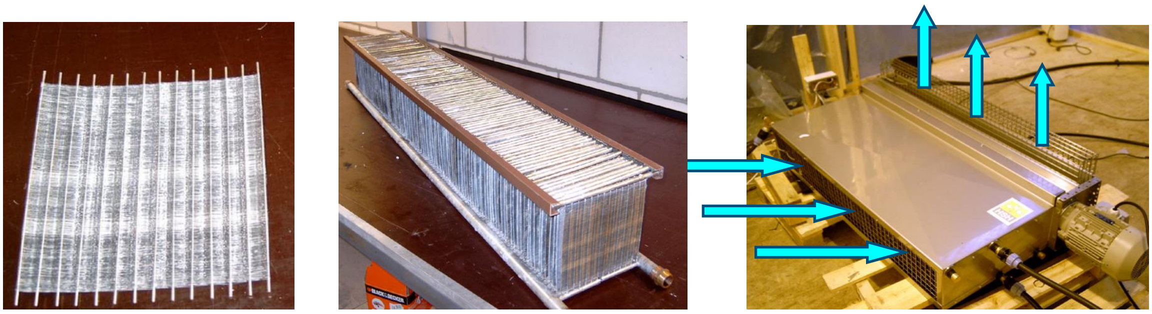

Fig. 2. Three stages of production of the heat exchanger: from left to right: copper capillaries with woven fine tin coated copper wires, combined in one block, final version with two blocks and ventilator.

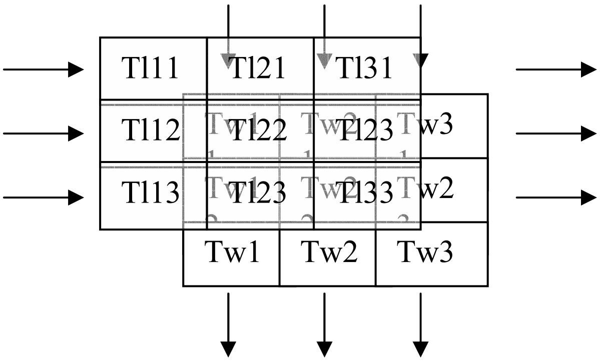

Fig. 3. Schematic presentation of the matrix model for the cross flow heat exchanger.

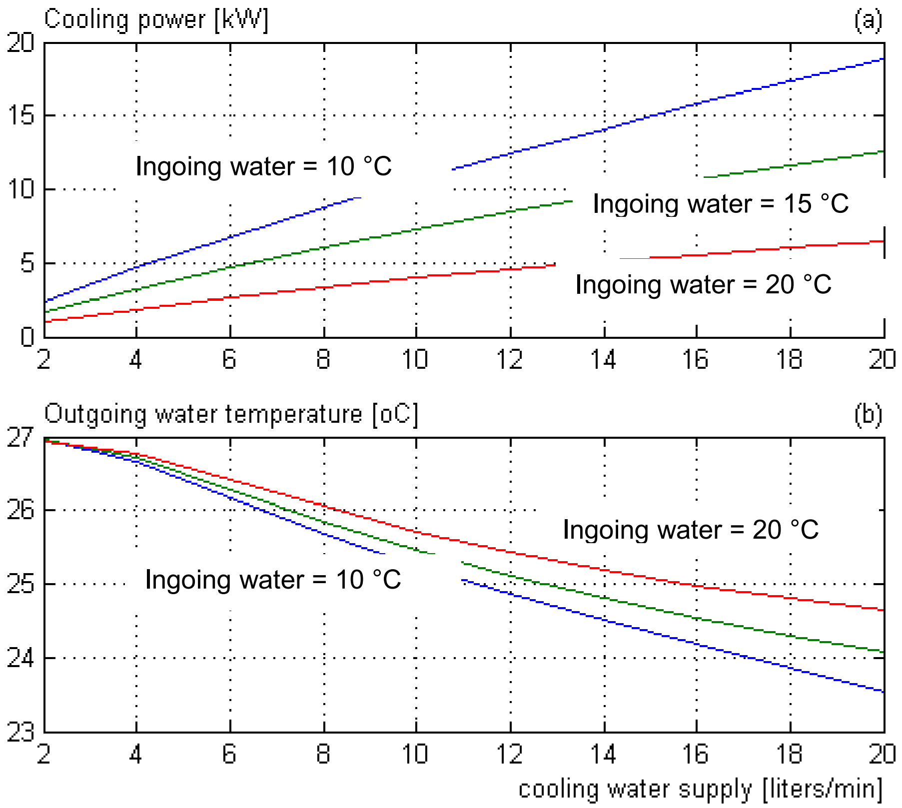

Fig. 4. Cooling power, outgoing water temperature of the heat exchanger at different water temperatures and flow rates.

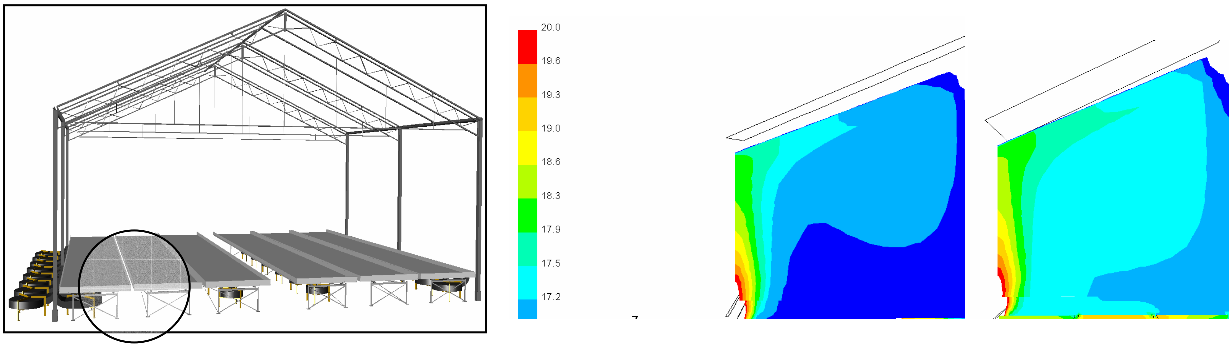

Fig. 5. Temperature pattern without (left) and with (right) 10 cm gap between the movable benches.

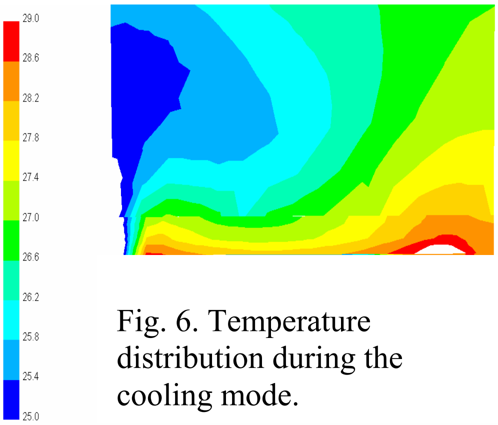

Fig. 6. Temperature distribution during the cooling mode.

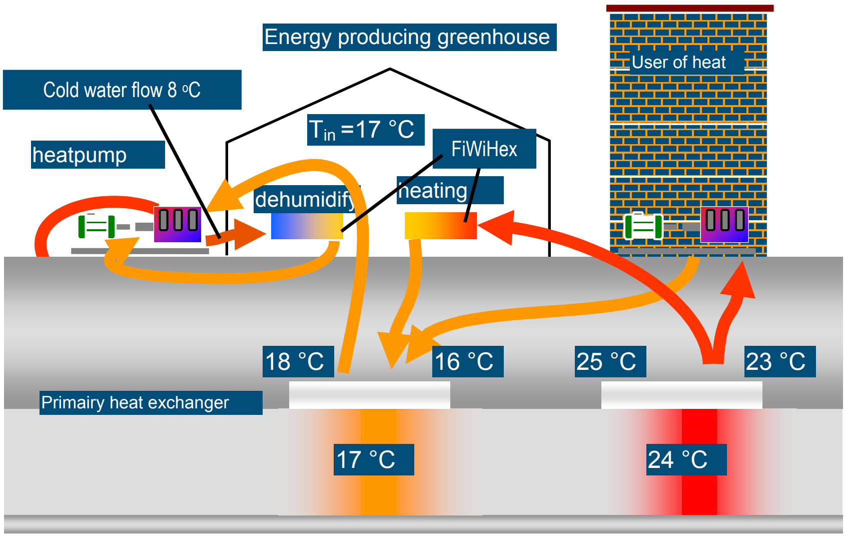

Fig. 7. Schematic lay out of the major components, heat fluxes and temperature levels of the final system.