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DESIGN OF AN EARTH TUBE HEAT EXCHANGER SYSTEM FOR GREENHOUSES

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ABSTRACT

An earth tube heat exchanger-storage system was designed and installed in a polyethylene clad double wall greenhouse, to reduce — under Western-European summer conditions — the inside air temperature to 14-17°C. The thermal mass of the soil was used as a heat buffer. The system consisted of non-perforated corrugated plastic drainage pipes, 12 m in length and 20 cm in diameter, buried at a depth of 2 m underneath the greenhouse. Groups of five pipes were gathered in a collector equipped with a fan. In this way the air can be circulated internally in the greenhouse – pipes system. The system allows to transfer excessive heat from the greenhouse air to the soil during hot summer days and to protect the greenhouse plants from freezing during winter.

KEYWORDS

Soil heat exchanger-storage system, thermal mass, heating, cooling, greenhouse, azalea, renewable energy.

INTRODUCTION

In Western Europe, greenhouses are primarily built to increase the air and plant temperatures, due to the so-called greenhouse effect. Under certain circumstances, however, optimal plant production requires the greenhouse to be cooled. It is well known that the flower quality of azaleas (*Rhododendron simsii*) enhances remarkably if the air temperature during the dormancy period is restricted to 14-17°C. Most conventional cooling systems, however, consume a lot of power or fossil energy. In this study, an effective low-cost system was designed which should enable to lower the inside air temperature to about 14°C under Belgian summer conditions and to increase the air temperature above freezing point during winter.

METHODS

The required cooling capacity was simulated using the Gembloux Dynamic Greenhouse Climate Model (Pieters and Deltour, 1997). To this end, simulations were carried out for the months May to October under Belgian circumstances (maritime climate), assuming a perfectly working cooling system. Different measures were assessed for their energy efficiency. Based on the data obtained in this way a system was designed and applied to a 100 m^2 plastic clad greenhouse, which corresponds to the size of an experimental greenhouse. The most important requirements of the system were a low consumption of non-renewable energy, the usability for both cooling and heating purposes, low maintenance requirements, easy applicability in practice (large-scale operation), its compactness (low space consumption inside the greenhouse), compatibility with standard greenhouse design, and the absence of adverse effects on plant growth and ergonomic aspects.

RESULTS

As a first step in energy efficient cooling or heating of the greenhouse, energy gains or losses must be restricted to a minimum. Since plant production needs solar radiation, transparent insulation is required. Therefore, a double polyethylene wall and roof were chosen. However, to further reduce excessive solar radiation levels during summer, a classic horticultural screen which reflects 80% of the available radiation, was necessary to obtain acceptable cooling capacities. In contrast to the situation in conventional greenhouses, the screen was designed for application at the outside, in order to keep the heat absorbed by the screen out of the greenhouse. The screens can be moved over the roofs, sidewalls and gables to adjust the inside radiation level according to the weather conditions. The simulations pointed out that in this way, the required cooling capacity dropped to about 150 W/m^2. Although this value is rather high, further reduction is highly hampered by the specific characteristics and requirements of greenhouses.

The two roof planes were designed to rotate around the ridge of the greenhouse ensuring the possibility of a large opening for natural ventilation. The roofs can be opened independently of the position of the outer screens. In this way, screening and ventilation can be combined to achieve the desired inside air temperature.

To cool the inside greenhouse air under the outside air temperature, two systems are mainly used: conventional mechanical cooling and evaporative cooling (pad and fan or fog). Mechanical cooling was excluded because of the high investment and exploitation costs and power consumption. The performance of evaporative cooling under Belgian circumstances, however, is mostly very poor, since during hot periods the weather is mostly very humid, so evaporative cooling is limited to at most 5-6°C under the outside air temperature. Another way to cool the air is making use of the thermal mass of the soil under a greenhouse. The soil temperature approaches an almost constant value of 10-12°C at a depth of about 2 m. To utilize this thermal mass, an earth tube heat exchanger system was designed. Such a system exists of buried tubes through which the inside greenhouse air is circulated by means of fans. During summer, the air is cooled via heat transfer to the ground, during winter cold air can be heated.

For stationary thermal conditions, the heat transfer characteristics of the earth tubes were modelled based on the general heat transfer equation of a single heat exchanger, thereby assuming that the soil temperature does not change along the tubes. To determine the overall heat transfer coefficient k_m of a tube, conductive thermal resistances were neglected. This means that the overall heat transfer coefficient k_m was assumed to equal the convective heat transfer coefficient α, which for non-perforated corrugated drainage pipes can be written as (Gnielinski, 1976):

$$\alpha = \frac{\lambda(F/8)(Re-10^3)\,Pr}{d\left(1+12.7(F/8)^{1/2}(Pr^{2/3}-1)\right)} \tag{1}$$

with	d	: diameter of the tube	[m]
	λ	: thermal conductivity of the air	[W/(m.K)]
	F	: friction factor	[-]
	Re	: Reynolds number	[-]
	Pr	: Prandtl number	[-]

As a compromise between friction losses in the tube and cost of the tube, a non-perforated corrugated tube with diameter 20 cm was taken. Under the given flow conditions, the friction factor F of the tube was 0.065 (Moody, 1944). With these parameter values, the temperature difference in the back section of the heat exchanger ΔT_2 relatively to the temperature difference in the front section of the heat exchanger ΔT_1 as a function of the tube length L and the air velocity v was given by:

$$\frac{\Delta T_2}{\Delta T_1} = e^{-0.0159(13.3-\frac{1}{v})L} . \qquad (2)$$

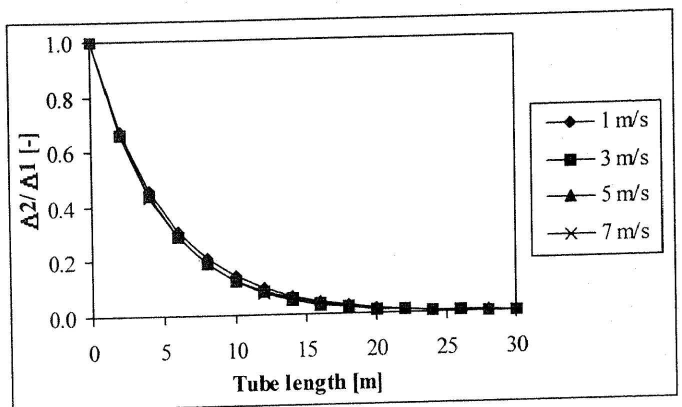

Fig. 1. Relative air temperature reduction as a function of tube length and air velocity.

Figure 1 points out that, under stationary thermal conditions, the relative air temperature reduction decreases exponentially with the tube length L. Puri (1986) and Gauthier *et al.* (1997) proved that under dynamic thermal conditions the total daily amount of energy stored or recovered per volume of soil decreases exponentially with tube length. On the basis of these findings, it was decided to restrict the tube length to approximately the greenhouse length, i.e. 12 m. The optimal air velocity in the tubes was chosen as 6 m/s as a compromise between friction losses (proportional to the square of the velocity) and the thermal capacity of the heat exchanger.

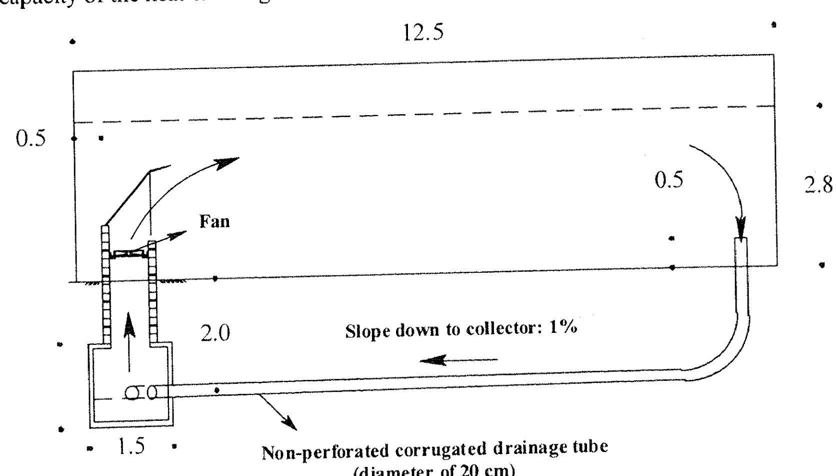

Fig. 2. Length-wise section of the earth tube heat exchanger-storage system.

With the chosen values of d, L, and v, the heat transfer rate per tube approaches 1.2 kW, assuming internal circulation of the air and a horizontal air temperature gradient of 5°C in the greenhouse. Consequently, 15 tubes with a pipe center-to-center distance of 0.5 m were to be buried parallel to the longitudinal axis of the greenhouse at a constant depth of about 2 m, which gives a maximum cooling-heating capacity of about 175 W/m^2. At this depth, earth tubes are mostly immersed in ground water. This improves the heat transfer characteristics of the soil (Puri, 1986; Van Caenegem and Deglin, 1998). The tubes were gathered in 3 collectors, each of them equipped with a fan to circulate the air internally. A length-wise section of the earth tube heat exchanger system of the greenhouse is given in Fig. 2. Figure 3 shows a top view of the heat exchanger system. In further research, experimental results will be compared with theoretical ones to investigate the performance of the heat exchanger under various climate conditions and control strategies.

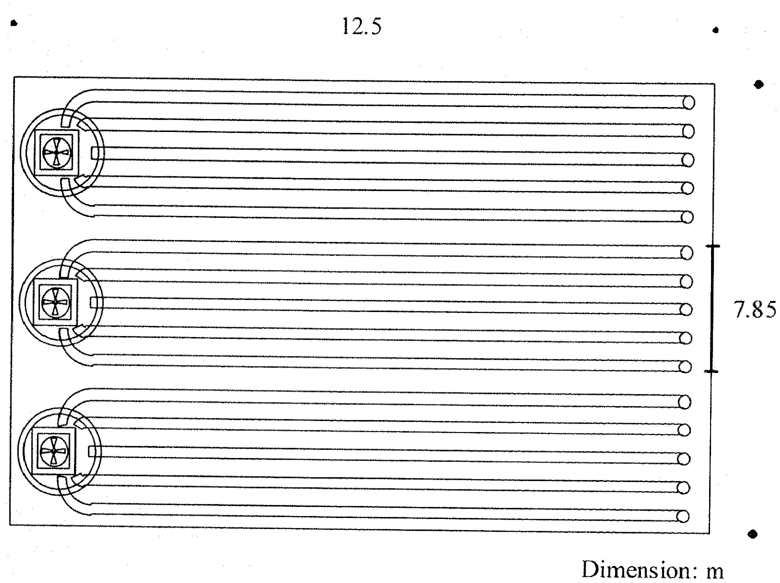

Fig. 3. Top view of the earth tube heat exchanger-storage system.

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