Greenhouse with an Integrated NIR Filter and a Solar Cooling System

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Abstract

The scope of this paper is a new greenhouse design that incorporates both a filter for rejecting near infrared radiation (NIR) and a solar cooling system. Cooled greenhouses are an important issue for the combination of high global radiation and high outdoor temperatures. As a first measure, this study prevents heat entering the greenhouse by applying a NIR-reflective cover material. The special spectral selective properties of these materials will block up to 50% of the outside solar energy from entering the greenhouse, which will reduce the cooling capacity required. The second measure is the introduction of a solar driven cooling system. When the NIR reflecting coating is designed as a parabolic or circular shaped reflector integrated in the greenhouse, the reflected solar energy received by a PV cell at the focus delivers sufficient electric energy to drive a fan and pad cooling system. The excess energy can be used for desalination and/or energy supply. Parameters related to typical climate conditions and energy flows are presented.

INTRODUCTION

In the northern countries, with colder winter climate conditions, energy saving is an important issue. Moreover during summer cooling is needed by natural ventilation to remove excess energy. In the southern countries with higher global radiation and higher outdoor temperatures during summer, cooling of greenhouses is even more important (Stanghellini, 1987). With the novel greenhouse design presented in this paper, cooling can be combined with energy supply. First developments applying linear Fresnel lenses were presented by Jirka et al. (1999) and Tripanagnostopoulos et al. (2004). Fraas et al. (2001) presented an illumination system with glass fibres. A schematic setup of the new design with a spectral selective mirror is depicted in Fig. 1. The advantage of this system is a very homogeneous and high illumination level in the greenhouse. The basic setup is an integrated NIR filter with a parabolic or circular shape that will focus the NIR radiation. First of all, it will prevent high radiation load during a period with high outdoor temperatures. Secondly, the focused radiative energy can be transformerd into electrical energy. This can be used, for example, for cooling the greenhouse with a pad and fan system and/or can be supplied for external use.

METHODS AND RESULTS

Covering Materials

Spectral selective materials were investigated with respect to light transmittance in the PAR part and reflection in the infrared part of the spectrum. Two applicable film materials with multilayer coatings, one metallic and one dielectric, were found with useful material properties. The transmission and reflection properties of these films are depicted in Fig. 2. The dielectric multilayer film shows a very good transmission in the PAR region and good reflection for a limited NIR area of 900-1200 nm. The metallic multilayer film shows a somewhat lower transmission in the PAR area and a good reflection for the whole NIR area of 900-2500 nm. For horticultural applications, we designed a special reflector that combines high PAR transmission with optimal NIR reflection. The implications for the climate conditions in greenhouses with a NIR reflecting film are given by Hemming et al. (2005).

Concentration of Thermal Radiation through a Light-Transmitting Mirror

A reflecting cover with parabolic or circular geometry will result in a maximum power level at the focal point. With a ray tracing computer program (Raypro) the optimal geometry of the reflector was designed. Furthermore the direct and diffuse transmission can be calculated from the optical data of the covering materials. Figures 3 and 4 show variants of different parabolic and circular reflectors. For the parabolic reflectors of Fig. 3, the complete reflector has to move with the elevation of the sun. With the parabolic geometry (Fig.4) the focal point (line) depends on the elevation angle of the solar radiation. The focal point moves in response to the position of the sun along a circle with the radius half of that of the circular reflector. An advantage of the cylinder concept is the relative simple control, because the movement of the focal point is only one dimensional. Raypro, the ray tracing program, calculates the total collected energy on a silicon solar cell. The efficiency of this solar cell is calculated to be 15% for the NIR region. The result of the calculations with silicon cells is presented in Fig. 5 for the three different design cases of Fig. 3 and 4. In Table 1, some characteristic energy values per greenhouse surface area are given for a clear summer day (25 June) in The Netherlands for the three system designs and a normal PV system as a reference. Due to the concentration factor of about 100, the required PV area is a lot smaller compared to multi crystalline silicon PV systems. The solar cells have to be cooled with air or water as described by Zondag et al. (2003).

Energy Balance

A computer simulation of the thermal balance of the greenhouse was used to predict the required cooling capacity. With the greenhouse climate simulation program “Kaspro” (Zwart, 1996) the energy balances are calculated on a warm summer day in the Netherlands. First the balance for a standard greenhouse is calculated and second a greenhouse covered with the NIR reflecting filter. The heat transport by conduction through the cladding material is neglected. The results are presented in Fig. 6 and 7. Comparing both figures, a strong reduction of the heat load can be noticed and a reduction of the plant transpiration is shown due to the reduced heat load. Despite this, a considerable reduction of the required cooling can be noticed. The peak cooling capacity decreases from 610 W/m^2 to approximately 300 W/m^2 and the total daily required cooling energy decreases from 21.7 MJ to 10.8 MJ/m^2.

Transformation of the Reflected Solar Energy to Cooling Energy

1. Cooling With Compression or Absorption Coolers. The feasibility of compression or absorption coolers can be roughly estimated. For the normal greenhouse the maximum heat load is 610 W/m^2. If the greenhouse is closed this heat load has to be cooled. The electric power for a compression cooler with a COP (Coefficient of Performance, ratio between heat extracted and electrical energy input) of 2 equals 610/2 i.e. 305 W/m^2. With the spectral selective NIR covering film the maximum heat load drops to 300 W. In this case, the required electric power for the cooler decreases to 150 W/m^2. An absorption cooling system powered by hot thermal oil heated by the concentrating solar collector system will have a COP of 0.4, so the maximum heat input is 610/0.4 or 1525 W/m^2. For the spectral selective NIR covering film the input power for the heat pump decreases to 300/0.4i.e. 750 W/m^2. The required cooling capacities for both coolers are too large for practical feasible projects.

2. Cooling With Fan and Pad. For both cases, with and without the NIR reflecting film, the effect of fan and pad evaporative cooling was calculated with a Mollier diagram in Mathlab for a greenhouse length of 50m. The evaporative cooling effect of tomato leaves was taken into account using the data of Stanghellini (1987) with a Leaf Area Index (LAI) of 2.5. The outside temperature was 25 ^{o}C and relative humidity 40%. Behind the pad (for instance company Munters, Celdek 5090-15), where 3.6 g of water was evaporated per unit air flowmass (kg/s), the temperature dropped to 17 ^{o}C at a humidity of 90%. In the case of a normal greenhouse covering the maximum radiation in the greenhouse is 600

W/ m^2. After a path length of 50 m and an air flow rate of 2 m^3/s per m width, the temperature increased to 25.9 ^oC. The maximum water consumption is 760 g/m^2 per hour (per m width and length of 50 m) and the daily value is 6.7 dm^3/m^2. In the case with the NIR reflecting film the maximum radiation in the greenhouse drops to 300 W/ m^2. Then the air flow rate can diminish to 1 m^3/s and the greenhouse air temperature increases to 24.9 ^oC. In Fig. 8 the temperature profile, the humidity and the evaporation of the tomato crop are presented across the greenhouse with length of 50 m. In Bartzanas and Kittas (2005) the air speed for an evaporative cooling system was 1.67 m/s with a pressure difference of 3 mm water head (30 Pa). Applying a pressure that is quadric with the flow rate and an efficiency of 60% will result in a maximum electrical power consumption of 5.2 W/m^2 without the NIR reflecting film. With the NIR reflecting film it reduces to 0.5 W/m^2. The instantaneous values of the electric energy consumption are presented in Fig. 9. The daily values of the energy consumption are 0.1 MJ/m^2 for normal greenhouses and 0.01 MJ/m^2 for greenhouses with the NIR reflecting cladding. The water consumption is given in Fig. 10; the maximum is 211 g/m^2 per hour, while the daily value is 1.8 dm^3/m^2. The effect of the NIR film halves the water consumption and the air flow rate which reduces electrical energy consumption by a factor ten. The results are summarized in Tables 2 and 3.

In fact, it can be concluded that the system generates more solar energy than needed to feed the fan and pad unit. The excess electrical energy might be used for a desalination unit or for supplying electrical energy to the public system. The most important advantages of the novel design of greenhouse with NIR reflective film are the considerable decreases in the consumption of electrical energy and water.

CONCLUSIONS

With a NIR-reflecting film the heat load inside the greenhouse can be reduced by a factor of two. Generally, the heat load in the greenhouse is too large for compression or absorption coolers, but with a fan and pad system it is feasible. With the combination of a NIR-reflecting film and the fan and pad system the excess heat load can be removed with minimal energy consumption. The NIR film halves the water consumption and the cooling air flow rate and this reduces electrical energy consumption by a factor of ten. The generated power of the photovoltaic cells at the focal point is sufficient to cool the greenhouse with a fan and pad system. The excess of energy can be used for desalination and/or energy supply.

ACKNOWLEDGEMENTS

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Tables

Table 1. Overview of electric energy yields of the designed systems.

	Peak Power* [W/m²]	Daily Energy Yield* [MJ/m²]
Global radiation	925	31
Reference PV	138	4.6
Parabolic reflector in E-W direction	41.7	1.3
Parabolic reflector in N-S direction	41.7	1.4
Cylindrical reflector in E-W direction	32.7	0.9

* Clear day June 25 the Netherlands (De Bilt).

Table 2. Overview of energy balance of the overall system.

	Maximum Power [W/m²]		Daily Energy [MJ/m²]	
	Normal	NIR-Film	Normal	NIR-Film
Global radiation	925	925	31	31
Energy yield cylindrical reflector		33		0.9
Heat load inside	610	300	21.7	10.8
Ventilation power	5.2	0.5	0.1	0.01

Table 3. Overview of the water use of the system.

	Maximum water flow [g/h m^2]		Daily water evaporation [dm^3/m^2]	
	Normal	NIR-Film	Normal	NIR-Film
Evaporated water by tomato crops	269	205	2.3	1.7
Evaporated water by pad and fan	211	97	1.8	0.8
Total water consumption	480	302	4.1	2.5

Figures

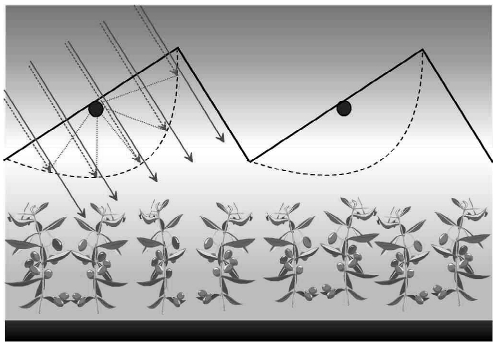

Fig. 1. Greenhouse with a spectral selective parabolic mirror (----) and a collector at the focal point, (——▶) indicate visual light, (······▶) indicate NIR radiation.

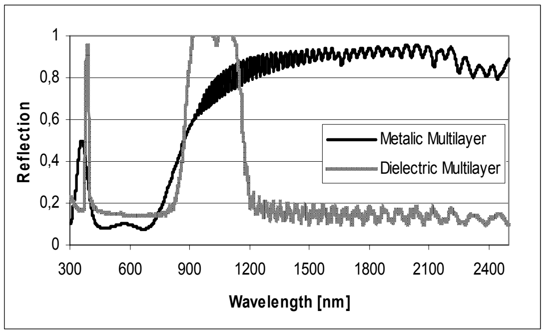

Fig. 2. Transmittance and reflectance of spectral selective reflecting multilayer polymer films.

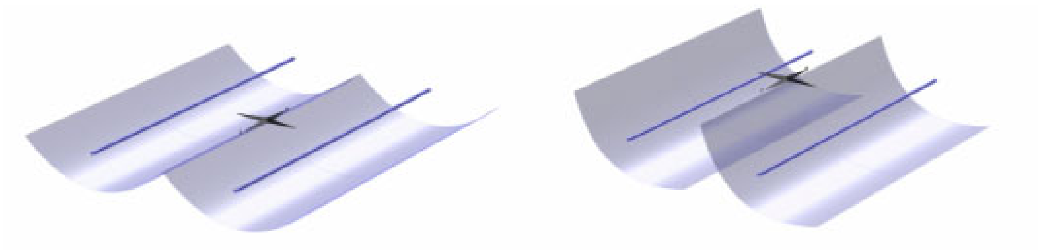

Fig. 3. Parabolic reflectors rotate in the East-West direction.

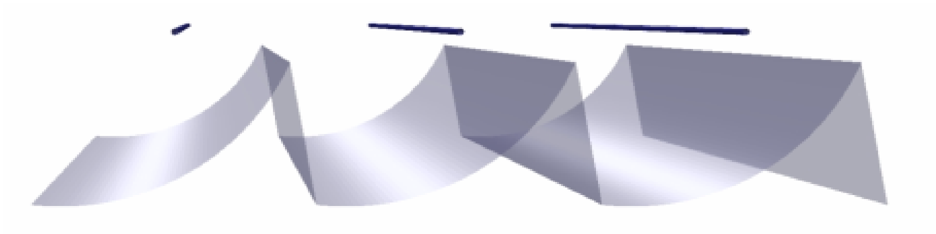

Fig. 4. Cylindrical reflector oriented in the North-South direction.

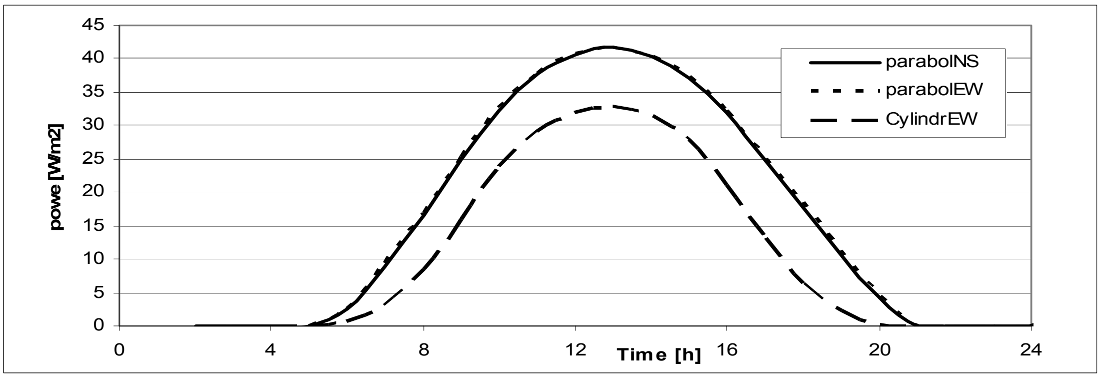

Fig. 5. Calculated results of the electrical power output on a clear day (June 25) in the Netherlands (De Bilt) of the Silicon PV cell at the focus of : a. Parabolic reflector with North-South orientation, b. Parabolic reflector with East-West orientation and c. Cylindrical reflector with East-West orientation.

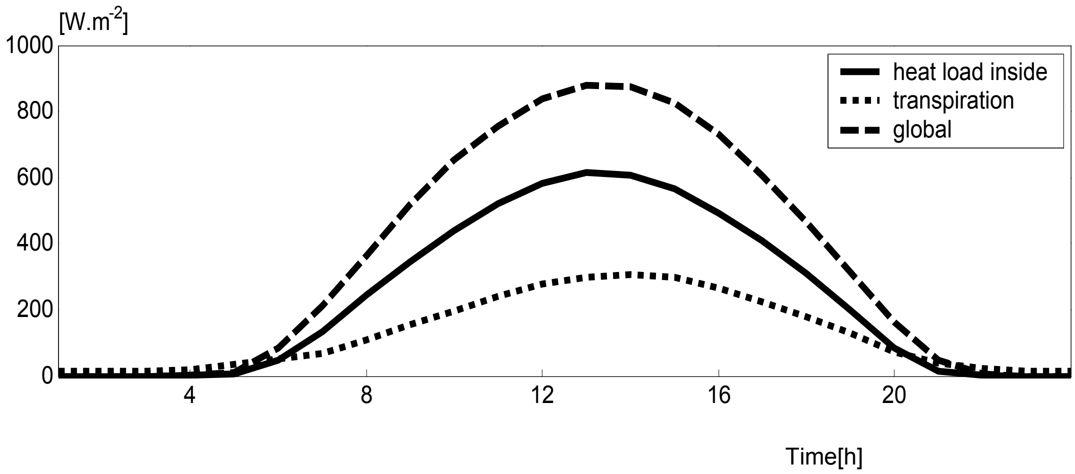

Fig. 6. The global radiation on a clear day (June 25) in the Netherlands (De Bilt), the heat load inside the greenhouse and the corresponding cooling effect by transpiration of tomato crops, calculated using the computer simulation program KASPRO.

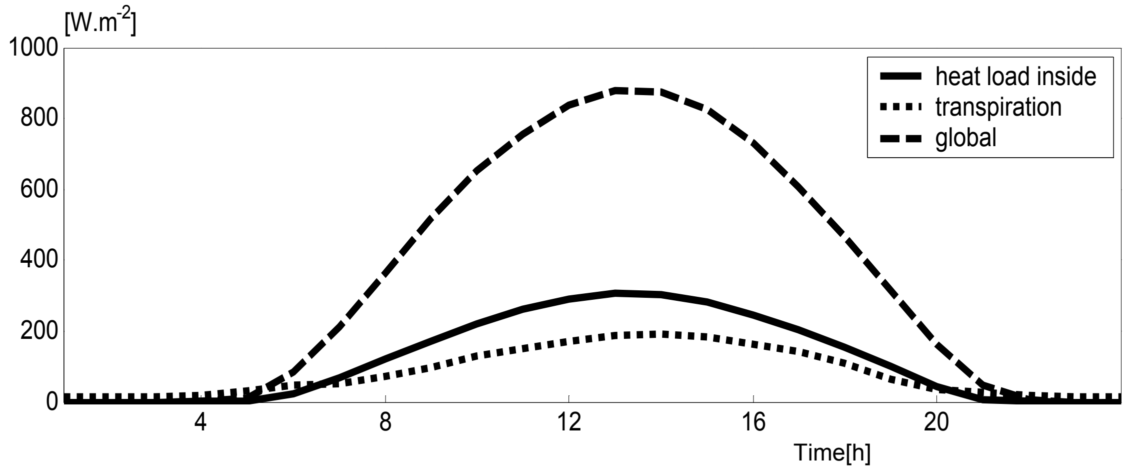

Fig. 7. The global radiation on a clear day (June 25) in the Netherlands (De Bilt), the heat load inside the greenhouse with a NIR reflecting filter and the corresponding cooling effect by transpiration of tomato crops, calculated using the computer simulation program KASPRO.

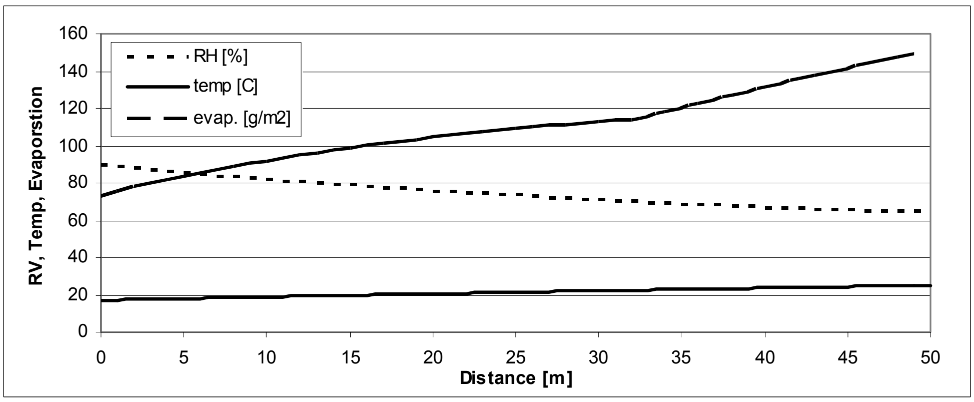

Fig. 8. Calculated temperature and humidity in a 50 m long greenhouse.

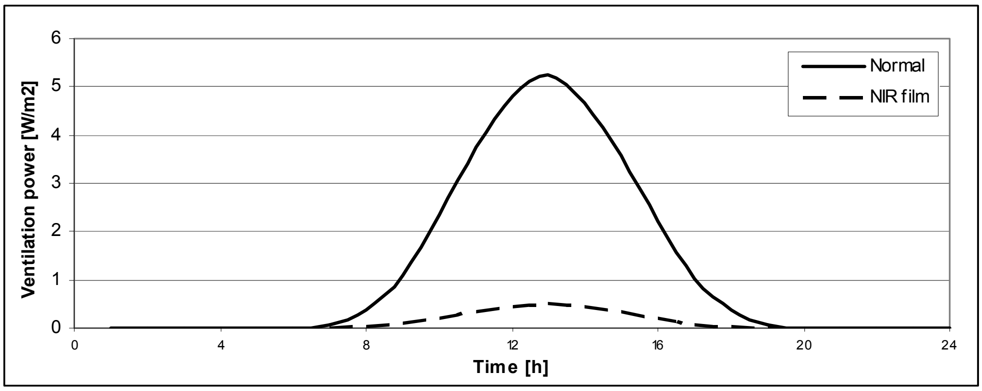

Fig. 9. Calculated results of the required ventilation power with and without the NIR reflecting filter.

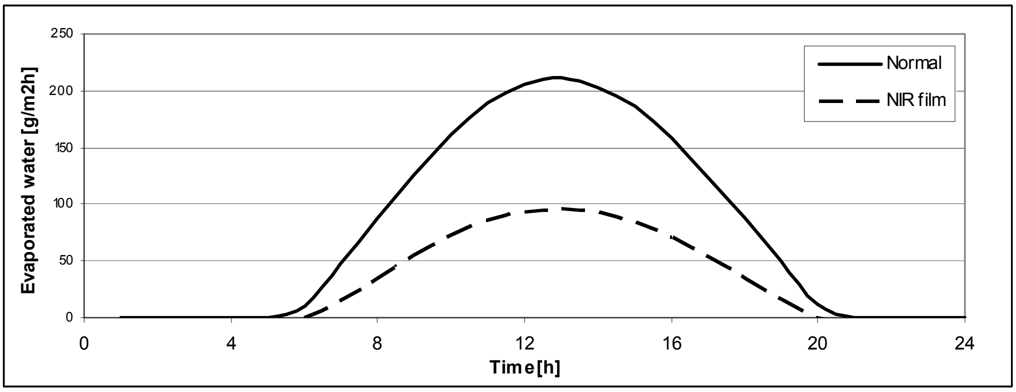

Fig. 10. Calculated results of amount of evaporated water inside the greenhouse with and without the NIR reflecting filter.