ENERGY CONVERSION OF CONCENTRATED NEAR INFRARED RADIATION IN A SOLAR GREENHOUSE

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ABSTRACT

The aim of this investigation was to develope a new type of greenhouse with an integrated filter. The filter reflects and concentrates the near infrared radiation (NIR) which is then converted to electric power by means of TPV cells. In northern countries, with colder winter climate conditions, energy saving is an important issue. Moreover, during the summer, cooling by natural ventilation is needed to remove excess energy. In the southern countries with high global radiation and outdoor temperatures during the summer, cooling of greenhouses is even more important [1]. An important issue is the concentration potential of the integrated reflector. In this study several approaches were investigated and a circular trough reflector appeared to be most suitable. The most important properties concerning concentration capabilities were investigated to come to an optimal concept regarding generated power, constructional limits and growing conditions. With the concept presented in this paper, cooling can be combined with power generation up to a an electric output of about 20 kWh annually per m² greenhouse on a yearly base. The produced electricity can be used for energy supply and/or for extra cooling with a pad and fan system and/or a desalination system. The concept will be worked out to an operating prototype.

INTRODUCTION

The design of modern greenhouses is based on a compromise between a maximised transmission of solar radiation, a minimised heat loss and minimised cooling requirements within an economical context. For northern latitudes, a high transmission is paid back in terms of high production potentials. For southern latitudes, cooling is important. [1].

The aim of this study was to develope a new type of greenhouse with an integrated filter, which reflects near infrared radiation (NIR, 750-2500 nm) and exploits the NIR radiation by means of thermal photovoltaic cells (TPV) in a solar energy system. With the innovative 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. [2] and Tripanagnostopoulos et al. [3]. Fraas et al. [4] 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 minimum of constructional parts which block the visible radiation and a minimum number of moving parts. In the first setup the focussing potentials of several concepts were studied with a ray tracing model. One of these concepts will be worked out to an operating prototype.

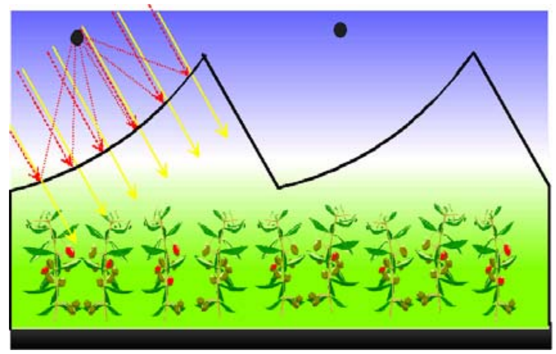

Fig. 1 Greenhouse with a spectral selective cylindrical concentrator and a collector with TPV cells in the focal point

METHODS

The momentaneous power output of the system is dependent on direct solar radiation and the concentration ratio under the circumstances. The power output of the system on a yearly base is the sum of all occurring circumstances during the year. In this study, for every hour of a typical Dutch climatologically year the azimuth and elevation of the sun are calculated. On the basis of these values the concentration ratio was obtained from a pre-generated table. This table contains the concentration ratio in relation to the angles of incidence. Given the direct solar radiation intensity and additional data such as the NIR fraction of global radiation and the efficiency of the TPV cells for NIR, the electrical output on each hour can be calculated. These results were summarized in the total electrical output per m² greenhouse surface on a yearly basis. All simulations in this study are done under the following additional conditions:

- The solar radiation was based on a typical Dutch climate
- The NIR fraction was assumed to be constant and 50% of the global radiation
- The collector width was 2,5% of the span width which is an acceptable loss of visible light for Dutch greenhouse horticulture
- The electrical efficiency of the TPV cells was 15% of the NIR radiation

- To take the angle of incidence on the collector into account, a refraction index of the collector was introduced and assumed to be 2. Yet, the given electrical efficiency of the TPV cells has taken the reflection at the surface into account and was therefore adjusted for the simulations.

All optical simulations were performed with the ray-tracing model Raypro [7], developed by Wageningen UR Greenhouse Horticulture especially for greenhouse material purposes. The model was based on ray-tracing in such a way that a large number of rays of light were traced from the light source trough the object (light-based). The model was able to consider an object as infinite (e.g. a large greenhouse). This is done by repeating the object infinite times. In this way side effects can be excluded.

RESULTS

The first step in the development of a new concept of concentrating NIR radiation in a solar greenhouse is to investigate the known principles of focussing in general. This has to be done for greenhouses where, depending on the type of crop and country, a low cost concept is crucial. As the sun's position changes continuously during the day and during the year, systems with a high concentration ratio require moving parts. Systems based on a parabolic concentrator must move together with the sun's position; other systems consist of a fixed concentrator with a moving collector.

The performances and feasibilities of several concepts were investigated with the ray tracing model. Especially the influence of the parabolic or circular trough geometry was studied with respect to the power output, complexity of the construction, controlling and economical feasibility.

With a parabolic dish concentrator a very high concentration ratio can be achieved. Because the focal point moves with both the azimuth and elevation of the sun, a major disadvantage of the parabolic dish is the need of movability in 2 dimensions. With a trough geometry however, the position of the focal point (which is actually a line) depends only on the elevation of the sun (see Fig. 2). The movement of the focal point, caused by the azimuth of the sun, only results in a longitudinal offset and is of minor importance in case of large greenhouses. Of course, the efficiency of the TPV cells will decrease with an increasing offset.

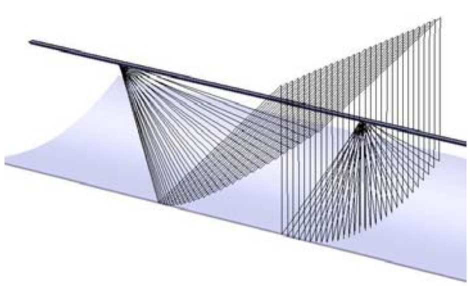

Fig. 2. Longitudinal independency of the angle of incidence of a trough concentrator

An major advantage of the parabolic trough reflector with respect to the circular trough reflector is the higher concentration ratio which is theoretically unlimited (see Fig. 4). Yet this requires continuous adjusting of the entire system. The major advantage of the circular trough concept is the fixed position of the reflector while adjusting only the collector in the focal point. A disadvantage however, is a limited concentration ratio (see Fig. 4).

Unlike a parabolic concentrator, the focal point is rather a focal area which negatively affects the concentration. Concentration is maximal at perpendicular incidence and decreases with an increasing offset to perpendicular incidence (see Fig. 5). Concentration also depends on the ratio between radius and width of the concentrator (RW-ratio) and decreases with an decreasing RW-ratio. In theory it is possible to achieve an infinite concentration ratio with an infinite RW-ratio. However, the focal point will have an infinite distance to the concentrator. In practice, the concentration ratio and an acceptable distance have will be a compromise.

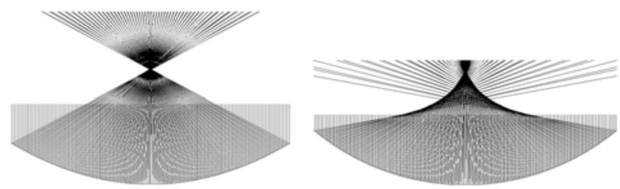

Fig. 4. Focus of a parabolic (left) and circular trough reflector at perpendicular incidence

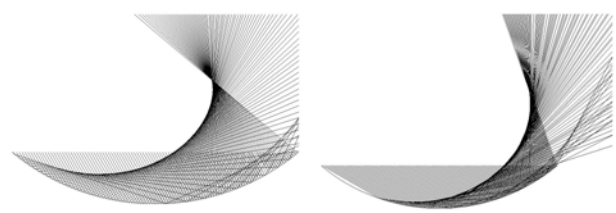

Fig. 5. Focus of a circular trough reflector at 30° (left) and 60° angle of incidence

In the case of a circular trough concentrator, the maximum power output will depend on the width of the collector compared to the width of the concentrator, because the focal point is rather a focal area. Also, the collector must be placed at the optimum position around the focal area. In this study, two methods for determining the optimal location of the collector were investigated. The first method assumes that the optimum position moves along a circle with a radius half of that of the concentrator. The second method determines the optimum position on the basis of iterative ray tracing based on maximum power output.

The first method proved to be suboptimal because the incoming light is partially blocked by the collector. Also a slight offset often increases power output because of more favourable angles of incidence, especially with high angles of incidence.

The electrical power output of the concept is dependant on a number of properties from which the following are optimized: the RW-ratio, the roof slopes on the south and north side, and the rotation of the collector given the optimum position (see Fig. 6).

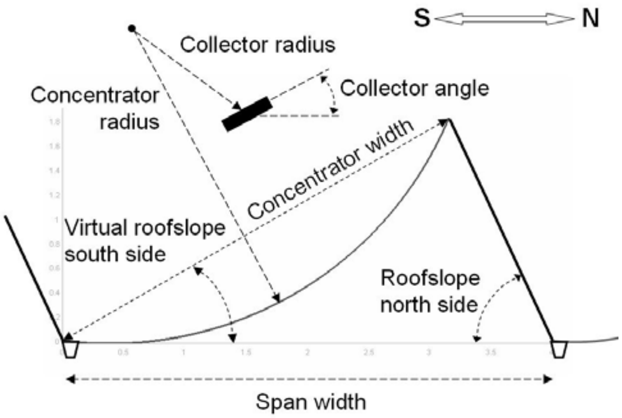

Fig. 6. Parameters of the concept which are optimized

Because of the large number of combinations the first optimizations were carried out with a tube collector instead of a flat plate collector. This was to rule out the collector's rotation angle. Also simulations with a 60° northern roof slope showed a decrease in power output of 10% compared to a 90° roof slope. A overall consideration regarding costs, natural ventilation and geometry turns out in favour of a 60° northern roof slope.

The results of the southern roof slope and RW-ratio optimization is shown in Fig. 7. The optimum is restricted by constructional limits. Draining problems during rainfall could occur in a hollow reflector. Also a high RW-ratio results in an collector which is located far above the greenhouse cover. An overall consideration results in a roof slopes of 30° and 60° for south and north side respectively at a RW-ratio of 1,5.

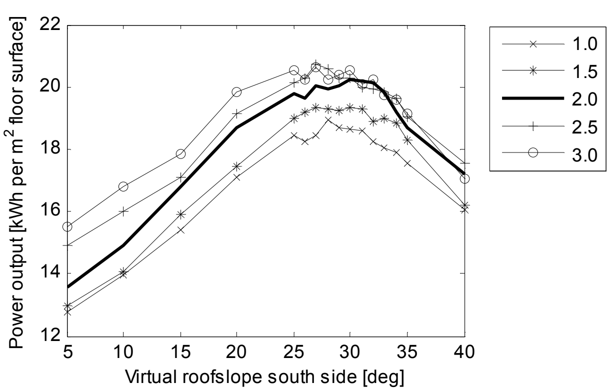

Fig. 7. Power output in relation to southern roof slope and RW-ratio, on base of a northern roof slope of 60°, a NIR reflectance of 100% and a collector width of 2,5% of the span width

Next, the collector angle is optimized with iterative ray tracing simulations. Results show a minor decrease of power output with a steady collector rotated 30° compared to an adjustable collector (see Fig. 8). Because of this there is no need for continuously adjusting the collector angle.

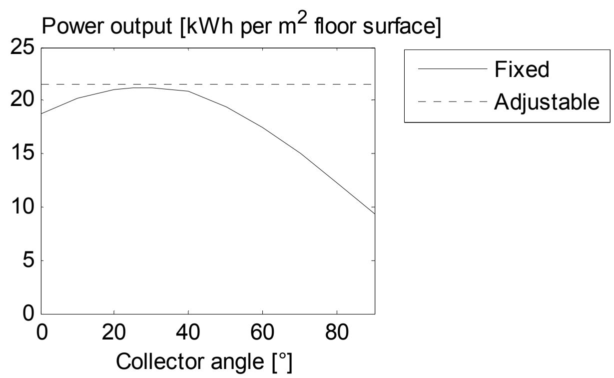

Fig. 8. Power output in relation to collector with a fixed angle compared to adjustable collector

To separate the NIR part of the spectrum from the visible part (Photo Active Radiation, 400-750 nm), existing and new materials were investigated with respect to light transmittance and NIR reflectance. The results are discussed in Sonneveld, Swinkels 2006 [6]. Due to the spectral selective properties of these materials 30-45% of the solar energy has to be reflected, which will drastically reduce the need for cooling of the greenhouse under summer conditions. The spectral reflection is shown in Fig. 9.

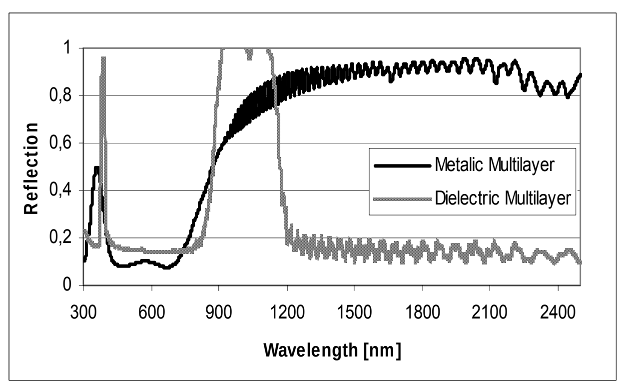

Fig. 9. Reflectance of two spectral selective reflecting multilayer polymer films

The conversion with TPV cells is compared to PV cells by comparing properties like Voc, quantum efficiency and fill factor of Ge, GaSb and Si cells. TPV cells in the focal point require cooling due to the high heat load of the concentrated radiation. An overview of the energy yield for different cells is given in Table 1.

Table 1. Overview of (T)PV materials and efficiency for radiation larger then 750 nm

Material	Band Gab [eV]	V_{OC} [V]	I_{SC} [mA/m²]	Power* [W/m²]	Eff* [%]
Ge	0.67	0.27	306	57.8	12.0
GaSb	0.74	0.37	173	45.8	9.5
GaSb (MOVPE)	0.74	0.35	274	70.0	14.5
CIS	1.05	0.51	172	63	13.1
Si	1.11	0.65	146	75.9	15.7

*) Part of the AM 1.5 solar radiation with wavelength larger then 750 nm

CONCLUSIONS

The concept of a greenhouse with integrated NIR selective concentrator with TPV cells in the focus point has the potential to generate an electric output of about 20 kWh annually per m² greenhouse, under the conditions and assumptions mentioned earlier. The south side of each span will consist of a circular trough collector with integrated NIR filter. The collector will have a virtual roof slope of 30° on the south side of a span, a 60° roof slope on the north side, a collector width of 2,5% of the span width and a RW-ratio of 1,5.

A computer simulation of the thermal balances of the greenhouse [8] was used to predict the implications for the climate inside the greenhouse. When NIR radiation is reflected by the special selective covering material, a reduced heat load remains. This results in a better climate in the case of high global radiation. The heat load into the greenhouse will be diminished by about a factor 2. This reduced heat load will also affect the transpiration of the crops according to the model of Stanghellini [1]. This reduced heat load also reduces water consumption, and makes it easier to cool the greenhouse with natural ventilation or pad and fan and improves growth conditions in the greenhouse [6].

The generated electricity can be used for energy supply and/or for extra cooling with a pad and fan system and/or a desalination system. The proof of principle will be tested in a prototype greenhouse with an area of about 100 m².

ACKNOWLEDGEMENTS

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