A SELF REGULATING GLARE PROTECTION SYSTEM USING CONCENTRATED SOLAR RADIATION AND THERMOTROPIC COATING

Adolf Goetzberger, Michael Müller, Manuel Goller
Fraunhofer-Institut für Solare Energiesysteme, Oltmannsstr. 5, D-79100 Freiburg, Germany, Phone: ++49-761-4588-152, e-mail: goetzb@ise.fhg.de

Abstract - A static, non-mechanical, self-activating sun protection system affecting only the direct sunlight but not the diffuse skylight is described. It is based on the selection of direct sunlight by concentration. A lens array in front of a glass pane concentrates the direct light onto a thermotropic layer where it increases temperature beyond the switching temperature and causes the thermotropic layer to become locally quasi-opaque. Most parts of the glazing except for the small focal regions remain transparent and contribute to the illumination of the room behind. The system performance is theoretically analysed by a numerical solution of the equation of heat conduction, giving the temperature distribution within the system. Different samples of the sun protection system, using different thermotropic materials and other system components have been constructed and measurements of various temperature and transmission properties have been performed.

1. Introduction

Exposed to high insolation, unprotected rooms with large glazing areas can show very uncomfortable situations because of overheating and glare problems. Therefore usually blinds and curtains are used as sun protection systems. These fulfill the protection requirements but often diminish the available daylight to such a poor level that artificial light has to be used in the rooms - despite of a high outside illumination! Additionally, all common systems need more or less error prone mechanical control for activating the protection feature. Thus, it would often be desirable to have a non-mechanical self-activating sun protection affecting only the direct sunlight but not the diffuse skylight.

Here, we report about design and construction of such a system [MUELL98] that was first described in [GOETZB98]. The direct sunlight is specifically selected by its property of being able to be concentrated - diffuse light cannot be concentrated. A lens array on the front of a glass pane concentrates the direct light onto a thermotropic layer. Thermotropic materials change their light transmission properties depending on the temperature. Thus, the concentrated radiation in the focal region leads to temperatures beyond the switching temperature and causes the thermotropic layer to be locally quasi-opaque. The concentrated direct light is partly reflected, partly diffusely scattered. Most parts of the glazing except for the small focal regions remain transparent and contribute to the illumination of the room behind. The changing solar position causes a corresponding movement of the small non transparent spots.

2. System Concept

The principle of the system concept is shown in figure 1. The different components are (in the order from the outer to the inner parts):

- A lens array for concentrating the incident direct sun light
- A thin layer protecting the thermotropic material
- The thermotropic layer itself
- An infrared absorbing layer serving for additionally heating the thermotropic layer (not shown in Fig.1)
- A pane on the exterior side for protecting the whole compound and a pane towards the room on the interior side serving as substrate for the thermotropic layer

![FIGURE 1: Principle of self regulating glare protection system.](image)

The materials of the single layers, of the lenses and the final pane may vary with different experimental set-ups. Mainly the physical properties of the thermotropic and IR absorbing layer have to be matched carefully to each other.

3. Properties of thermotropic coatings

Thermotropic materials change their optical properties as a function of temperature. In a state called "unswitched" the layer is transparent for visible light. If the temperature is raised above the switching point, the layer becomes white, the transmittance
drops and no more visual contact to the surroundings is possible. The thermotropic effect of certain materials is caused by the separation of at least two polymer components with different refractive indices. Below the switching temperature the components are completely mixed and the system is fully transparent. Above the switching temperature a phase separation takes place and microparticles with diameters of the order of magnitude of the wavelength of visible light emerge. Because of the different indices of refraction of the separated phases, strong scattering of light takes place. As a result, the originally transparent blends of polymers become opaque.

Presently, there are two different kinds of thermotropic materials, hydrogels and polymer blends. A hydrogel consists of a water soluble polymer that is homogeneously mixed with water in a crosslinked gel as the second component. Because of their high content of water, these hydrogels can only be used when filled between two glass panes. Pure polymer blends, on the other side, are available as thin layers that can be coated onto a single pane. One component of the polymer blends, the polypropyleneoxide PPO, is embedded in a matrix consisting of another polymer. As references, see e.g. [GEORG98], [NITZ98], [WATAN98]. The transmission spectra of a hydrogel and a polymer blend for different temperatures are given in figures 2 and 3. The temperature dependence of the switching properties of different thermotropic materials in different spectral regions are shown in figure 4. For the practical application envisaged here it is decisive that the decrease in transmittance is large within a small interval of temperature.

4. Theoretical analysis of system performance

4.1 General considerations

For predicting the shading effect caused by the thermotropic switching, one needs an expression for the temperature distribution within the thermotropic layer as a function of the solar irradiation, the optical properties of the lenses and the physical properties of the thermotropic layer itself. This temperature distribution then determines the spatial distribution of the transmission properties of the system.

The temperature distribution can be found in four steps:
1. Determination of the spectral properties of each of the single components of the thermotropic compound.
2. Calculation of the heat generated in each of the single
components of the thermotropic compound by absorption of incident radiation, using the correspondent spectral data.

3. Calculation of the modifications of the homogeneously incoming solar radiation field by the action of the concentrating lenses.

4. Solution of the differential equation of heat conduction, using the results of the preceding calculations and the appropriate boundary conditions. This step is needed for calculating the temperature distribution in the whole compound, starting from the temperatures in the individual focal regions, which are known as results from the preceding steps.

The solution of the heat conduction equation gives the temperature distribution within the thermotropic compound in spatial resolution.

4.2 Spectral properties of the system components

The transmission and reflection spectra of the whole compound have been measured. The corresponding spectra of the single system components have been determined analytically using transmission and reflection laws and the Fresnel formulae. Therefore, a test ray is sent into the system of layers and splits multiply into reflected and transmitted parts. For each part one can calculate the single reflections \( R \), the single transmissions \( T \) and the corresponding overall quantities reflectance \( \rho \) and transmittance \( \tau \). The extinction and consequently the thickness of each layer is explicitly taken into consideration. Figure 5 shows the principles of this scheme (as reference, see e.g. [DUFFIE91], [GOETZB93]).

\[ \begin{align*}
\text{incoming single ray} & \quad \text{reflectance} \quad \rho \\
& \quad \text{reaction} \\
& \quad \text{extinction} \\
& \quad \text{cathode} \\
& \quad \text{R: single reflection} \\
& \quad \text{T: single transmission} \\
\end{align*} \]

\[ \begin{align*}
\text{air} & \quad \text{exterior pane D} \\
& \quad \text{thermotropic layer TTS} \\
& \quad \text{substrate pane SUB} \\
& \quad \text{air} \\
\end{align*} \]

**FIGURE 5:** Transmission and reflection of a light ray in a multiple system of dielectric layers (only the most important single reflections \( R \) and single transmissions \( T \) are taken into account).

4.3 Heat generated by irradiation of the system

Starting with a spectrally resolved solar irradiation \( S(\lambda) \), given in \( \text{W/m}^2/\text{nm} \), the heat generated in each of the layers of the whole compound can be calculated using the spectral data as generated in 4.2. All terms of volume absorption of a single test ray including all multiple reflections emanating from it are summed up. The spectral region refers to solar radiation and extends from \( \lambda_1 = 300 \text{ nm} \) to \( \lambda_2 = 2500 \text{ nm} \). As results for the heat \( W \ [\text{W/m}^2] \) generated in each of the layers of known thickness one gets the following expressions, where the two glass panes are now distinguished as \( D \) for the exterior pane and as \( \text{SUB} \) for the thermotropic layer’s substrate. \( R_1 \) denotes the reflection of the incoming ray at the exterior glass pane, \( R_2 \) is

\[ \begin{align*}
\text{sample T22:} & \\
& \text{2 mm glass} \\
& \text{thermotropic layer} \\
& \text{low-e layer} \\
& \text{6 mm glass} \\
\end{align*} \]

**FIGURE 6:**

- d: Measured transmission and reflection properties of the thermotropic compound T22 (4 mm float glass, polymer blend, low-e layer, 6 mm float glass).
- a, b, c, e: Corresponding calculated properties of the individual layers.
- IR ... infrared absorbing layer; TTS ... thermotropic layer
- \( R_1 \) ... reflection of incoming ray between air and exterior glass
- \( R_2 \) ... reflection between thermotropic and IR layer.

\[ \begin{align*}
\text{FIGURE 6:} & \\
& d: \text{Measured transmission and reflection properties of the thermotropic compound T22 (4 mm float glass, polymer blend, low-e layer, 6 mm float glass).} \\
& a, b, c, e: \text{Corresponding calculated properties of the individual layers.} \\
& \text{IR ... infrared absorbing layer; TTS ... thermotropic layer} \\
& R_1 \ldots \text{reflection of incoming ray between air and exterior glass} \\
& R_2 \ldots \text{reflection between thermotropic and IR layer.} \\
\end{align*} \]
the reflection between thermotropic and IR layer. Other reflections are much smaller because of less difference in the indices of refraction of adjacent layers and are not taken into consideration.

\[ W_D(\lambda) = \int \frac{(1-R_1)(1-T_D) + (1-R_1)(1-T_D)}{1-R_1R_2T_D T_{TTS}} d\lambda \]

\[ W_{TTS}(\lambda) = \int \frac{(1-R_1)(1-T_{TTS}) + R_1R_2T_D T_{TTS}}{1-R_1R_2T_D T_{TTS}} d\lambda \]

\[ W_{IR}(\lambda) = \int \frac{1}{1-R_1R_2T_D T_{IR pane}} d\lambda \]

\[ W_{substrate}(\lambda) = \int \frac{T_{IR} + R_1T_{IR pane}}{1-R_1R_2T_D T_{IR pane}} d\lambda \]

Here, A and B denote the following expressions:

\[ A = S(1-R_1)(1-R_2)T_D T_{TTS} \]

\[ B = S(1-R_1)(1-R_2)T_D T_{TTS}(1-T_{IR}) \]

The total heat generated in the thermotropic compound in dependence of the incoming radiation S is then given as:

\[ W_{Compound}(\lambda) = W_D + W_{TTS} + W_{IR} + W_{SUB} \]

4.4 Irradiation by concentrated solar radiation

4.4.1 Analytical derivation of the concentration function

For determining the modification of the spatial energy distribution of the homogeneously distributed incoming solar radiation by the concentrating lenses one has to know the ratio between the lens aperture and the focal region and the distribution of the radiation flux within the focal region itself. A method has been developed for obtaining these information. An imaging function associates each location (r) of a ray hitting the surface of the lens with the corresponding image position (r’) in the focus. Using spherical lenses, as an example, circular rings of incoming radiation are transformed into circular rings in the focal region. The concentration for such a situation is given as the ratio of the corresponding ring surfaces. In this way, the concentration effect of a lens can be given as a function in spatial resolution. Figure 7 shows the cylindrical co-ordinates used.

With \( O(r) \) being the surface function of the lens, \( O'(r) \) its first derivative with respect to r, \( n_1 \) the refractive index of the surrounding medium (air) and \( n_2 \) the refractive index of the lens, the focal position \( r' \) of a location \( r \) on the lenses surface can then be calculated with geometrical optics as a function of \( r \):

\[ r' = r - \frac{O(r)}{\tan \gamma(r)} - \frac{f_{real}}{\tan \gamma - \arcsin \left( \frac{\cos \gamma}{n_2} \right)} \]

with

\[ \gamma(r) = \frac{\pi}{2} - \arctan(O'(r)) + \arcsin \left( \frac{\cos \gamma}{n_2} \sin \arctan(O'(r)) \right) \]

The spatially resolved concentration function is given as the inverse expression of the imaging function A(r):

\[ c(r') = \lim_{\Delta r' \to 0} \left\{ \frac{\left[ A_+^{(r') + \Delta r'} - A_+^{(r')} \right]^2}{2\Delta r' + (\Delta r')^2} \right\} \]

\[ + \left\{ \frac{\left[ A_-^{(r') + \Delta r'} - A_-^{(r')} \right]^2}{2\Delta r' + (\Delta r')^2} \right\} \]

For practical reasons, this complicated expression has been approximated by suitable fitting functions.

4.4.2 Raytracing derivation of the concentration function

The concentrating effects of various lenses have been simulated using raytracing methods. As an example, figure 8 shows the concentration factor of an aspherical lens.
4.5 Temperature distribution in the system

The temperature profile in the thermotropic compound is obtained as a solution of the equation of heat conduction with internal heat source:

\[
\frac{\partial \bar{T}(r, \phi, z, t)}{\partial t} = \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \bar{T}(r, \phi, z, t)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \bar{T}(r, \phi, z, t)}{\partial \phi^2} + \frac{\partial^2 \bar{T}(r, \phi, z, t)}{\partial z^2} \right) + \frac{W(r, \phi, z, c(r'), S)}{\rho c_p}
\]

This equation has been solved numerically.

4.6 Numerical solution of the temperature distribution equation

In order to predict the performance of the thermotropic compound in various situations, an appropriate simulation model has been designed. An optical simulation (ray tracing) yields the focusing effect of the lens array and a thermal simulation determines the effect of the concentrated radiation. Numerical solution of the heat conduction equation gives the spatially resolved temperature distribution. Therefrom, the distribution of the transmission properties of the compound follows. Figure 9 gives an example of a thermal simulation using the simulation programme CFX-F3D. The centre lens is circularly surrounded by six other lenses that have no outer neighbours. The thermal simulation result clearly reflects this asymmetrical initial spatial situation.

Figure 9: Result of the numerical solution of the temperature distribution equation for sample T22 with focusing lens L4 (aspherical glass lens), as seen from the room side. Temperatures are given in °K; the incoming irradiation is 1000 W/m².

Figure 10 shows for different samples the simulated temperatures and temperature differences at the surface of the compound as function of the heat produced in the focus. The sample structures are as follows:

- T22 ... glass, TTS, IR, glass
- T23 ... PMMA, TTS, IR, glass
- T36 ... PMMA, TTS, IR, PMMA

Dependent on the lens and type of sample, temperature differences up to 10 K can be realised. This is sufficient for reaching the switching temperatures of the thermotropic compound within the focal regions and to maintain the
4.7 Performance criterion
There are many possible combinations between type of thermotropic compound and dimension and type of concentrating lenses. An evaluation criterion has been established that assumes minimal values when the maximal temperature reached is comparatively small and when at the same time the temperature difference between adjacent zones is large. The evaluation expression is:

\[ K_L = \frac{T_{L,\text{max}}^2}{\Delta T_L} \]

Here, \( T_{L,\text{max}} \) is the maximum focal temperature, depending on lens type L. \( \Delta T_L \) denotes the temperature difference between maximum temperature in the focuses and minimal temperature in the intermediate region. Concerning this criterion, sample T36 in figure 10 fits best to these conditions. T36 consists of two PMMA panes. Because of their smaller thermal conductivity this leads to larger temperature differences than in the other samples T22, T23 with at least one glass pane.

4.8 Conclusions from theoretical analysis
From the theoretical analysis, we can state the following requirements for the design of a useful thermotropic compound:
- Basically, the thermal masses should be kept small in order to allow switching even for low solar altitudes.
- Especially the exterior and interior (substrate) pane should be thin and of low thermal conductivity.
- An additional layer of high absorptance in the solar infrared spectral region can enhance the switching performance of the thermotropic layer.

5. Realisation

5.1 The thermotropic compound
In first experiments small compound areas with single lenses were tested in order to examine the conditions necessary to achieve the desired effect. With the most appropriate available samples, a window of larger area (0.4 m x 0.6 m) has been constructed. Its structure is:
- 4 mm exterior glass pane, serving as support for a
- 1mm layer of thermotropic polymer blend
- IR absorber (low-e coating) on a
- 6mm glass pane as outer protection

5.2 The observation box
A box shown in figure 11 was constructed to serve as a test room for different daylighting elements. The aperture oriented towards the sun can be adjusted in inclination angle. Thus, vertical facades can be simulated as well as roof with different inclinations. The face opposite to the window has a small opening for visual inspection and for installation of measuring equipment (illuminance/irradiation and luminance/radiance meter).

FIGURE 11: Observation box serving as test room for daylighting elements. The element’s inclination angle can be adjusted relative to the sun.

6 Measurements

6.1 Temperature distribution
The surface temperature was measured in the whole window area when the window was oriented vertically towards the sun. In this position, the thermotropic layer shows the best switching performance. The various time dependent states of the system have been recorded using an IR camera. Figure 12 shows a state when the thermotropic layer has already switched.

FIGURE 12: Measured temperature distribution for a thermotropic compound after having switched (hydrogel).
6.2 Temperature dependence of the switching process
The temperatures measured show that the thermotropic layers with switching temperatures in the interval between 25° and 30° C are heated up sufficiently by absorption of concentrated radiation in the focal region. There, the layer switches and consequently the transmission is strongly reduced. The occurring temperature differences are sufficient for maintaining a switched state only in the focal points. The temperature of the whole compound, however, rises with constant irradiation. This means that after longer irradiation times the thermotropic layer switches over its whole area.

6.3 Time dependence of temperature
At selected locations, the time dependence of temperature was measured. Figure 13 shows the results. The temperature differences between the focal regions and the intermediate spaces adjust to (3.5 ± 0.5)° C.

6.4 Time dependence of transmission
The switching process does not take place instantaneously. For a description of the system performance, the time dependence has to be taken into consideration. The transmission in the focal region was recorded vs. time, see figure 14. After 2 minutes, the reduction in transmission was nearly complete. This is fast enough for obtaining the maximum transmission reduction at the illuminated spot before its position changes by the solar movement.

6.5 Angular dependence of switching properties
It is important to study the switching properties of the compound in dependence of the varying angles of solar irradiation. Measurements showing the time necessary for switching were performed with window orientations relative to the sun ranging from 0° (vertical incidence) to 15°. The horizontal axis of the window remained always normal to the sun. The results for different lens types are shown in figure 15.
Figure 16 shows that a south oriented polymer blend compound at the location of Freiburg in Germany (48° N) becomes active from March to September from 11:00 to 13:00, respectively. A hydrogel compound functions during the whole year from 10:00 to 15:00.

Figure 16 sketches the time boundaries approximately. In the morning it takes a longer time till the compound has heated up sufficiently while in the afternoon it is already warmer and maintains a switched state with an irradiation less than 600 W/m² even after 15:00. With the compound switched completely over the whole area, it takes the polymer blend several hours without direct radiation till it becomes completely clear again. This means that the polymer blend, once switched, can maintain the sun protection function even after 15:00, although the solar irradiation is not sufficient to induce the switching process for an otherwise unswitched compound. The hydrogel has a much faster back switching time of approximately 30 minutes only. Additionally the switched state can be maintained with less radiation than in the case of the polymer blend.

7 Conclusions

It has been shown experimentally that a static, non-mechanical, self-activating sun protection system affecting only the direct sunlight but not the diffuse skylight can be constructed by concentrating direct sunlight onto a layer of thermotropic material. A careful theoretical analysis of possible system performance was necessary in order to choose well adjusted properties of each of the single system components. This analysis involved determination and calculation of the components’ spectral properties, of the heat generated within the components by absorption of the incident radiation, of the modification of the homogeneous solar radiation field by the action of the concentrating lenses and of the resulting heat conduction within the system. Then, the resulting temperature distribution in the whole compound when exposed to solar radiation can be determined as a function of the system components’ properties.

It is crucial to choose well adjusted system components in order to reach the switching temperature of the thermotropic material within the focal regions of the concentrated direct solar radiation and to maintain the temperature difference between focal and non-focal regions necessary two different states of transmission, opaque and non-opaque.

It could be seen that systems using thermotropic materials based on hydrogel generally showed a better performance than those using polymer blends. The time needed for reaching the switching point is shorter and the angular domain of solar positions where the system could provide its sun protection function is larger. After longer periods of irradiation, each system switched not only locally but completely due to heat conduction. The hydrogel showed a much faster back switching time.

Before practical realisations of sun protection systems as described can be used in buildings, more detailed simulations and experimental work has to be performed. These should involve in particular studies of different concentrating lens types and of different means to absorb concentrated heat to the right spots in the thermotropic layer. Of great importance is the heat conduction of the transparent boundary layers of the thermotropic film.
<table>
<thead>
<tr>
<th>References</th>
<th>Authors</th>
<th>Title</th>
<th>Journal/Book Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOETZB93</td>
<td>Goetzberger A. and Wittwer V.</td>
<td>Sonnenenergie, Thermische Nutzung, 2nd edn.</td>
<td>Teubner, Stuttgart</td>
</tr>
<tr>
<td>GOETZB98</td>
<td>Goetzberger A.</td>
<td>Zwei neue Konzepte zum Blend- und Sonnenschutz.</td>
<td>11 Int. Sonnenforum, Köln, pp 440 - 445</td>
</tr>
<tr>
<td>MUELL98</td>
<td>Müller M.</td>
<td>Untersuchung thermostroper Schichten unter konzentrierter Solarstrahlung für selbstschaltende Blendschutzsysteme.</td>
<td>Diplomarbeit, Fakultät für Physik, Universität Freiburg</td>
</tr>
<tr>
<td>WATAN98</td>
<td>Watanabe H.</td>
<td>Intelligent window using a hydrogel layer for energy efficiency.</td>
<td>Solar Energy Materials &amp; Solar Cells 54 pp 203 - 211</td>
</tr>
</tbody>
</table>