Tropical and Subtropical Greenhouses – A Challenge for New Plastic Films

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Abstract

In subtropical and tropical regions it is necessary to get a cooling effect if high irradiation heats up the greenhouse. It is possible to use covering materials, which contain absorbing, reflecting, interference, photo- or thermochromic pigments.

Reflecting and coloured films containing absorbing pigments intercept PAR and give a shading effect throughout the year. More intelligent materials with interference pigments are able to reflect parts of the NIR more selectively. Photo- and thermochromic materials are in principle able to keep out NIR only during periods with high irradiation.

For the subtropics there is a need for thermic films, which prevent the transmission of FIR during cold nights and so create an insulating effect.

INTRODUCTION

In tropical regions plant production can take place throughout the year. However, heavy rainfall and wind affect the production in the open field on one hand and high tempertures and high humidity limit the production in greenhouses on the other hand. Adapted greenhouse systems are requested, where the covering has to match the following requirements:

- sufficient transmission for photosynthetic active radiation
- sufficient cooling effect;
- sufficient shading / diffusing effect;
- anti-drop condensation;
- anti-dust;
- no rapid ageing caused by ultraviolet radiation, mechanical, thermal or chemical (by pesticides) degradation;
- strength against wind;
- tightness against insects;
- low costs.

In subtropical regions the greenhouse additionally has to prevent heat losses even in unheated greenhouses. The covering material has to be tight for far infrared radiation to prevent heat losses especially during cold clear nights (Zabeltitz, 1999).

The most important requirement for greenhouse covering materials in the tropics and subtropics is to contribute to a cooling effect inside the greenhouse. Because high outside irradiation leads to an enormous heating effect inside the greenhouse, the covering has to anticipate too high temperatures by keeping out as much solar radiation as possible. This can be done by reducing photosynthetically active radiation PAR (400-700 nm). Furthermore there are materials contributing to a shading and diffusing effect within the greenhouse. To reach a cooling effect within the greenhouse it is much more effective to keep out all solar radiation that is not contributing to plant growth. Near infrared radiation NIR (700-3000 nm) is not necessary for plant photosynthesis. It is a challenge for a new generation of covering materials to keep out selectively this part of the solar spectrum.

Furthermore the heat loss through the covering is important for subtropical regions. If materials have a high transmission for far infrared radiation FIR (3000 -

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100000 nm), the heat loss from the greenhouse can be high and the plant temperature can drop. Therefore thermal materials are recommended to block the FIR.

There are different principles to fulfil these requirements with modern high-tech materials. The possibilities and limitations of present and future materials are explained.

COOLING AND SHADING EFFECT OF MATERIALS

Caused by high irradiation in tropical and subtropical regions the greenhouse inside temperature can rise above the absolute maximum temperature of most plants of 35^oC to 40^oC (Zabeltitz, 1999). It is necessary to get a cooling effect by the covering material. Moreover, the plant leaf temperature can rise 10^oC above air temperature, which causes damage of photosynthesis machinery, heat stresses etc. (Vonk Noordegraaf and Welles, 1995). Cooling, shading and diffusing effects are essential to decrease greenhouse air temperature, plant temperature and to avoid direct burning of plant leaves, flowers or fruits and to improve the uniformity of the light intensity inside the greenhouse. These effects can be reached by several roofing materials based on the principles of absorption, reflection, interference, photo- and thermochromism.

Reflecting Materials

In order to cause a shading effect in greenhouses covering materials are available containing reflecting pigments. These pigments consist of finely dispersed metal plaques in a polymer. Depending on the type of metal, parts of the solar radiation are reflected (Daponte, 1997). The light transmission of the material is decreased. Most reflecting materials are not selective, they just reduce the total PAR and so lead to a shading effect. Unfortunately, they reflect the solar radiation also during times of low irradiation, e.g. raining season, when it would be desirable to have more light transmission. It would be advantageous to have intelligent materials, like those based on interference (0) or photo- (0) and thermochromism (0), which show less reflection during these periods.

Absorption Materials

There are some horticultural plastic films on the market containing absorbing pigments in order to reduce light transmission and therefore lead to a shading effect. As a solar beam falls onto the material surface, part of the radiation is absorbed, while the other part is transmitted. Materials containing absorbing pigments are coloured if the absorption process takes place in the visible part, they are transparent if the absorption process takes place in the ultraviolet part or infrared part of the spectrum.

Materials containing absorption pigments in the visible part of the spectrum VIS (380-780 nm) display the same colour in reflection as in transmission, while the absorbed colour is complementary. Depending on the amount of pigment in the polymer, the PAR is lowered (Daponte, 1997). Main purpose of these materials is shading. There are many coloured plastic film materials on the market, in violet, blue, green, red, etc. (Fig. 1). Sometimes they are also used for photomorphogentically purposes (Hoffmann, 1999). By absorbing parts of the solar energy the energy flux into the greenhouse is reduced, of course. Therefore these materials not only lead to a shading effect but indirectly also to a cooling effect. However, absorbing pigments are not preferable for tropical climates because the absorption process in the material increases the plastic film temperature. Part of this absorbed energy is emitted as heat radiation into the greenhouse and will lead to a rising inside temperature. Thus, the cooling effect of absorbing materials is lowered.

Besides absorption pigments in the visible part of the spectrum, there are also materials acting in the near infrared part NIR (700-3000 nm). Main purpose of these materials is cooling. Since many years scientists and companies are working on covering materials to reduce the greenhouse inside temperature significantly. Since about 1939 water films have been used for the limitation of maximum temperature in glasshouses and it has been generally considered that the absorption of infrared radiation was the main means by which this was achieved (Brown, 1939). Investigations to optimise the water-roof-system followed, also $CuSO_4$-solutions and other coloured solutions in fluid-roof-systems were used to reduce NIR more selectively (Morris et al., 1958) (Fig. 2). However, there are no plastic films containing NIR-absorbing pigments available yet.

Interference Materials

There are also modern materials contributing to a cooling effect of the greenhouse based on the interference principle. Interference pigments consist of several layers of thin films on top of each other that all have different refractive indices. When a beam of white light strikes a very thin material with a thickness approximately equal to the wavelength of visible light, the incident light beam is split up into different rays by reflection at the upper and lower interface. The recombination of the individual rays from each side of the film leads to minimum and maximum intensities for certain wavelengths. These intensity differences are perceived by the eye as colours (Daponte, 1997) (Fig. 4). Interference pigments used for applications in horticulture consist of thin mica particles, which are coated with a thin layer of TiO_2. They selectively reflect parts of the incident light and transmit the rest. The colour of these pigments is determined essentially by the thickness of the coating of TiO_2. Furthermore, the interference effect is also influenced by the angle of incidence. Normally the pigment causes the highest light transmission if radiation is falling perpendicular on the pigment surface since no reflection occurs then. Assuming the absorption of the pigment is zero, the transmission will be one hundred percent (Daponte, 1997). Considering the roof shape of a greenhouse and the changing angle of solar radiation during the day and the year, the orientation of the pigment particles in the polymer can theoretically be optimised. If the sun is standing low in the sky in the morning and the pigment is brought into the polymer so that solar radiation is falling perpendicular onto the pigment, no reflection will occur, the transmission will be at the maximum. If the sun is then rising, solar radiation is falling onto the pigment with a smaller angle of incident, reflection will increase and the transmission will be reduced. Hence it is necessary to bring the interference pigment into the polymer in a special orientation. With the multi-layer interference technique it is theoretically possible to produce advanced coverings leading to a major cooling effect in the greenhouse if they are acting selectively in the near infrared spectrum.

There are commercial plastic film products containing interference pigments, which reflect parts of the visible part of the spectrum and therefore lead to a shading effect. Moreover they give a diffusive character to the film (Verlodt et al., 1995). New generations of interference plastic films act more in the NIR, the reduction of PAR is much smaller. These films lead to a significant reduction in greenhouse inside temperature, especially during the hottest periods of the day (Verlodt and Verschaeren, 1997) (Fig. 5). Moreover, there are glass materials with interference coatings acting very selectively in the NIR and transmit almost all PAR. These materials are used for heat reflection and therefore cooling in civil buildings (Prinz Optics, 1999) (Fig. 6). However, such materials are not available for horticultural practice yet due to high costs.

Photochromic Materials

Keeping out parts of the solar radiation depending on the angle of incident is only one possibility to cause a cooling and / or shading effect in the greenhouse. A second method is to keep out parts of the solar radiation depending on radiation intensity. Adding a photochromic effect to the covering material can cause this. Photochromic materials become darker or change colour under the influence of radiation with a special wavelength. When radiation is removed they return to their original state (Lozano-González, 1996). Photochromism can be defined as a reversible transformation of chemical species, induced in one or both directions by electromagnetic radiation, between two states having observable light absorptions in different regions. The activating radiation generally is in the ultraviolet region (300-400 nm). The reverse reaction can occur by thermal mechanism in some systems or the photochemically induced forms are thermally stable in others. In such systems the reverse reaction is predominantly photochemical. Spiro-oxazines have excellent photochromic properties and are therefore often used for variable-transmission materials such as photochromic lenses (Fig. 7). They are resistant to photodegradation also under continuous irradiation (Crano and Guglielmetti, 1999).

Photochromic materials are commercially available. They are for example used for sunglasses. The first generation of photochromic lenses had a light transmission of 80% in a broad spectrum of visible light (Fig. 8), which decreased to 48% (35°C) to 14% (10°C) when activated. The activation process took up to 10 minutes and was depending on temperature (Fig. 9). Today's photochromic pigments show higher transmission, faster responses and less temperature dependence (Crano and Guglielmetti, 1999).

Photochromic pigments are also available for horticultural greenhouse coverings. Japanese prototypes were tested by Lozano-González (1996). They found higher yields (up to 40%) on lettuce covered with polyethylene plastic films containing photochromic additives due to a higher efficiency of PAR transmission, which improved carbon dioxide assimilation. Moreover, the lifetime of the film was increased because UV radiation is absorbed by the pigments and converted into visible light (Lozano-González, 1998).

Thermochromic Materials

Besides keeping out parts of the solar radiation depending on the angle of incident or radiation intensity a third method is depending on temperature. If materials change colour over a defined temperature range they are called thermochromic. Removing the affecting temperature can return the process (Farina, 1998). Thermochromic materials are produced on basis of liquid crystal thermography. Fundamentally, a liquid crystal is a thermodynamic phase that is between the pure solid and pure liquid phases of matter and exists in some organic compounds under certain conditions. At temperatures below the event temperature the thermochromic liquid crystal will be in the solid state and will appear transparent. When it is at his event temperature, illuminated by white light (380-780 nm) the materials will reflect a unique wavelength of visible light; the eye will recognise a special colour. As the temperature rises through the material's bandwidth the reflected colour of the material will change. Finally, when the temperature exceeds the material's clearing point temperature, the material will enter the pure liquid state and will revert back to being transparent. This phenomenon occurs both on heating and cooling and is reversible. Typical materials are available with event temperatures ranging from 10°C to 120°C and bandwidths from 1°C to 20°C (Farina, 1998; Parsley, 1991). It would be useful to have thermochromic pigments with a bandwidth as wide as possible and an event temperature of around 60°C to 80°C to use them in greenhouse covering materials. These materials would then mainly act as shading materials. It is a challenge for the chemical industry to develop thermochromic pigments, which only change their NIR transmission and not the transmission for PAR, depending on irradiation and outside temperature.

There are thermochromic window films commercially offered consisting of a polymer-water solution sandwiched between thin plastic skins. If temperature decreases the polymer in the film elongated into diameters smaller than the light's wavelength, allowing light to pass freely through the film; the light transmission is 90%. If the film's temperature increases to about 75°C the polymer diameters become greater than the light's wavelength, light is reflected; the light transmission of the material is reduced to 20% (Suntek, 1998). Until now these materials are used for skylights but not for horticultural covering materials due to high costs.

INSULATION EFFECT OF MATERIALS

Especially for the subtropics the heat transfer through the covering is important. If materials have a high transmission for far infrared radiation FIR (3000 nm -1 mm), the heat losses from the greenhouse by radiation are high and the plant temperature can drop. The FIR is the radiation produced by every warm body that is cooling down. In unheated greenhouses warm plants exchange FIR with the colder environment. Damage can occur during cold, clear nights when inside greenhouse temperature can drop below outside temperature caused by the FIR losses through the covering material. In principle polyethylene (PE) does not have the capacity to absorb FIR. Therefore it is necessary to add additives (mineral fillers) or Vinyl Acetate (VA) (Waaijenberg and Verlodt, 2000). The percentage of FIR lost through the material is called thermicity (Feuilloley et al., 1990). A greenhouse film with a thermicity factor lower than 20% is a “thermic” material

Mineral fillers have a good heat retention capacity, so that the thermicity of polyethylene can be reduced to 20%. The addition of mineral fillers, however, affects the light transmission of the film. Another option is the use of Ethylene Vinyl Acetate co-polymers (EVA) instead of pure polyethylene. The higher the percentage of VA, the lower the thermicity will be. The light transmission is not affected. The percentage of VA can not be raised unlimitedly in a mono-extruded film because of creep (continuous stretching of the film at constant loading); the film becomes too elastic. Therefore greenhouse films are actually co-extruded (Fig. 3). In a co-extruded greenhouse film a middle layer with a high VA content can be combined with outside layers with a low VA content, so that the total film has good thermic properties and stays within the limits for creep.

Both PE plastic films stabilised for FIR and EVA films are commercial available with a thermicity varying between 15% and 35%.

CONCLUSIONS

Shading and cooling of tropical and subtropical greenhouses is quite possible by choosing the right covering material. Coloured plastic films containing absorbing pigments are available, which reduce PAR hence contribute to a shading effect. Plastic films containing interference pigments are able to reduce NIR and therefore also lead to a cooling effect in the greenhouse. In the future more intelligent materials can be expected to get even higher potential to reduce greenhouse inside temperature during periods of high irradiation. Improving interference materials and introducing photo- and thermochromic materials into horticulture are ways to go.

The interference effect is very much depending on the angle of incident of solar radiation. This fact should be used to optimise the orientation of the interference pigment in the polymer, so that the best heat reflection occurs at high irradiation. Photochromic materials are also able to reduce PAR transmission with increasing irradiation. They would be even more advantageous by being able to reflect NIR instead / additionally to PAR. Further, there are possibilities to use thermochromic materials in the future if their event temperature and their bandwidth are made suitable for greenhouse application.

For subtropical regions the combination of NIR reflection during the day with interception of FIR during the night is essential.

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Figures

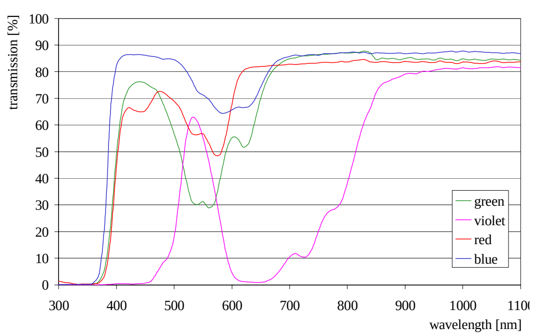

Fig. 1. Transmission of materials containing absorption pigments in the visible part of the spectrum (measurements ITG Hanover, Germany).

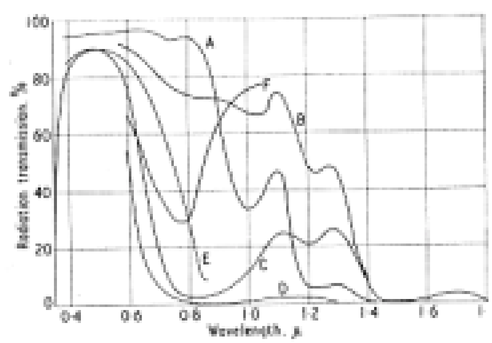

Fig. 2. Transmission of materials containing absorption pigments in the near infrared part of the spectrum (Morris et al., 1958).

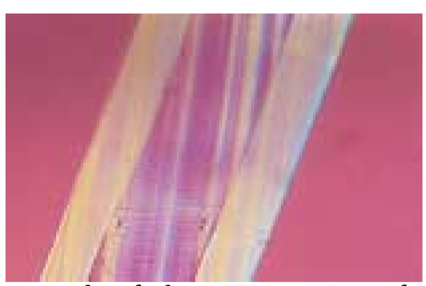

Fig. 3. Microscope photograph of the cross-section of a multilayer coextruded plastic film

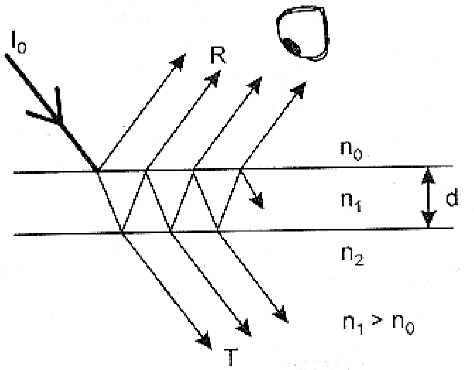

Fig. 4. Interference principle (Daponte, 1995).

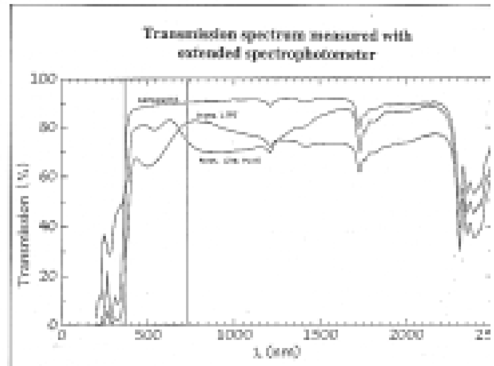

Fig. 5. Transmission of interference plastic films acting in the visible and near infrared part of the spectrum (Verlodt and Verschaeren, 1997).

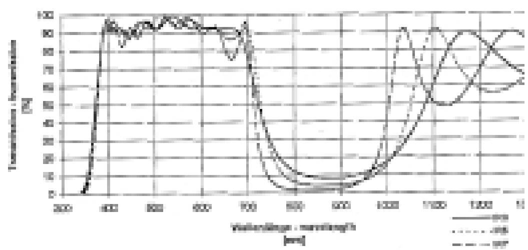

Fig. 6. Transmission of glass with interference coating acting selectively in the near infrared part of the spectrum (Prinz Optics, 1999).

Fig. 7. Scheme of a photochromic pigment (Crano and Guglielmetti, 1999).

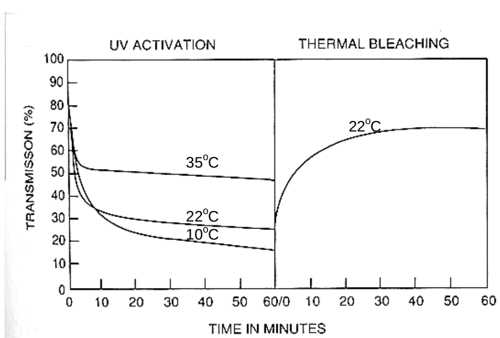

Fig. 8. Transmission spectrum of Transitions® lens activated and deactivated (Crano and Guglielmetti, 1999).

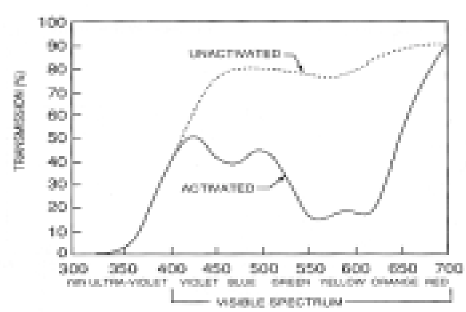

Fig. 9. Photochromic reaction of Transitions® lens (Crano and Guglielmetti, 1999).