Polymeric Thermotropic Materials for Overheating Protection of Solar Collectors

Dissertation

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ABSTRACT

Polymeric materials offer a significant cost-reduction potential for solar thermal collectors and may thus benefit a broader utilization of solar energy for various heating purposes. However, the long-term service temperature of plastics is limited. Thus, for potential applications of cost-efficient plastics in flat-plate solar collectors an appropriate design including overheating protection is essential. A feasible way to control stagnation temperatures in an all-polymeric solar collector would be the application of thermotropic glazings, which reversibly change their light transmittance from highly transparent to light diffusing upon reaching a certain threshold temperature. Appropriate thermotropic materials were not developed and investigated yet. Thus, the overall objective of this dissertation was to provide basic knowledge on the development and characterization of thermotropic layers for overheating protection purposes in all-polymeric solar collectors. Specific focus was given to the establishment of a fundamental understanding of relationships between the material formulation and structural parameters and the light-shielding properties of thermotropic layers, based on sound principles of polymer physics and materials science as well as solar physics.

For that purpose (1) an evaluation and strength-weakness analysis of existing thermotropic layers produced from polymeric materials concerning their applicability in solar collectors was carried out, (2) thermotropic prototype-layers were developed and designed for solar collector applications considering aspects of polymer physics, (3) thermotropic prototype-layers were characterized as to relevant morphological parameters and performance properties, (4) structure-property relationships between the performance properties and the inner material structure and formulation parameters of thermotropic prototype-layers were established, and (5) the effect of thermotropic prototype-layers on the efficiency of an all-polymeric flat-plate collector was investigated and modeled.

A review on various thermotropic glazing materials with respect to their ability to meet requirements for overheating protection of a solar thermal collector showed that the systems designed so far have to be adapted and optimized for solar collector applications, especially regarding their switching temperatures and long-

term stability. Among different thermofunctional materials, thermotropic systems with fixed domains (TSFD) were observed to possess the highest development potential for overheating protection applications in solar collectors. In TSFD scattering particles (also referred to as additives), which exhibit a sudden change of refractive index upon reaching a threshold temperature, are statically embedded in a matrix material (in general in a thermoset resin).

A methodological approach for the selection of a matrix material appropriate to the production of TSFD was defined, which included the determination of cross-linking parameters (curing rate, degree of cure) and the glass transition temperature of the resin material. Using exemplarily a UV-curable urethane acrylate resin it was shown that applying Dielectric Analysis (DEA), Attenuated Total Reflectance spectroscopy (ATR) and Dynamic Mechanical Analysis (DMA) relevant performance properties of a matrix material can be derived.

For a systematic investigation on TSFD for solar collector applications numerous prototype-layers were prepared by variation of base resin and additive type and concentration. TSFD prototype-layers were characterized concerning solar optical properties of the thermotropic layers in the clear and opaque state, and the switching temperature and transition temperature range. Furthermore differences in refractive index of matrix and additive, additive concentration and scattering domain size, shape and distribution were investigated. The ascertained morphological parameters were related to the light-shielding performance of the layers. Moreover, relationships between properties of formulation ingredients and the switching characteristics of the thermotropic layers were established. The overheating protection performance of the thermotropic layers in an all-polymeric solar collector with twin-wall sheet glazing and black absorber was evaluated applying theoretical modeling.

In the clear state the TSFD prototype-layers exhibited a hemispheric solar transmittance between 76 and 87%, with diffuse fractions ranging from 14 to 71%. Switching from the clear to the scattering state occurred at temperatures between 40 and 80°C. Transition temperature ranges between 10 and 25 K were recorded. Above the switching threshold the hemispheric solar transmittance changed to values ranging between 62 and 85%, with diffuse fractions between 36 and 78%.

Pronounced differences in refractive index >0.04 between matrix and scattering domain above the switching temperature were detected to be advantageous for the light-shielding efficiency of the layers. The most efficient additive concentration for the considered thermotropic layers was observed to be 5 m%. A uniform additive distribution across the film thickness was found to benefit the back-scattering efficiency. Thermotropic layers formulated with additive types exhibiting a short chain length displayed roughly spherical scattering particles with diameters between 0.5 and 3 µm and a moderate reduction in hemispheric solar transmittance along with a significant increase of diffuse solar transmittance. Additive types with long-chain molecules developed anisotropic scattering domains resembling contorted disks with a diameter up to 50 µm and a thickness between 100 and 400 nm. These disk-like scattering features yielded enhanced light-shielding properties.

The highest solar back-scattering efficiency of the TSFD prototype-layers in the opaque state was detected for material types based on resin types which exhibit a higher cross-linking density and low chain segment mobility (high glass transition temperature). Thermotropic layers produced from a resin with a wide-meshed network and low glass transition temperature exhibited the most distinct increases of diffuse solar transmittance above the switching threshold. The light-shielding efficiency of thermotropic layers being formulated with non-polar additive types increased with increasing molecular mass of the additives. The comparison of the additives thermal transitions with the switching characteristics of the thermotropic layer revealed an excellent correlation. This allows for tailoring the switching temperature and transition temperature ranges by selecting adequate additives.

As to the application of the produced TSFD prototype-layers for overheating protection of solar collectors it was found that compared to the use of the functional materials on the absorber, their utilization in the glazing maximized the efficient collector working temperature range and minimized stagnation temperatures. Thermotropic layers were found to reduce the maximum absorber temperatures to values between 129 and 146°C. Stagnation temperatures below 130°C would allow for the application of cost-efficient plastics as absorber materials.