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Selection of thermotropic materials for overheat protection of polymer absorbers

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Abstract

Thermotropic materials offer the potential to provide passive overheat protection for polymer solar absorbers. These materials are comprised of a matrix in which a second material, referred to as the scattering domain, is dispersed as small particles. Overheat protection is provided by a change in transmittance and reflectance at elevated temperature. The magnitude of this change depends on the change in the relative refractive index between the matrix and the scattering domain, the volume fraction and size of the dispersed particles, and the thickness of the material. To predict the effect of these parameters on the normal-hemispherical transmittance and reflectance, thermotropic materials are modeled as a non-absorbing slab comprised of discrete, anisotropic scattering, spherical particles embedded in a matrix material. A Monte Carlo ray tracing algorithm predicts the transmittance and reflectance of the slab. The model predictions are compared with: the analytical solution for a slab of non-absorbing, non-scattering media, and the measured transmittance of 0.3 mm thick polymer samples containing 400 nm particles. A parametric study of the effects of the design parameters on the transmittance is presented to identify potential material combinations which will produce a thermotropic composite capable of providing overheat protection for flat plate solar collectors. Relatively short chain alkanes or low molecular mass polyethylene in a matrix of polycarbonate are identified as promising materials.

Keywords: Thermotropic; Monte Carlo; Overheat protection; Polymer absorber

1. Introduction

Residential buildings account for approximately 27% and 22% of total energy consumption in the EU (European Commission, 2011) and the US (US Energy Information Agency, 2011), respectively, and are a major contributor to global emissions of CO_2 due to the reliance on fossil fuels for electricity and heating (European Commission, 2011; US Energy Information Agency, 2011). Solar thermal systems have tremendous potential to displace the use of fossil fuels as an energy source in residential buildings because a large fraction of energy consumption is for space heating and hot water. In northern and central European countries, such as Denmark, Germany, and Austria, 86–92% of household energy consumption is for space heating and hot water (Weiss and Biermayr, 2006). In the US, 57% of the energy consumed in residential buildings is for space heating and hot water (US Energy Information Agency, 2009).

Despite the potential of using solar thermal systems to meet space heating and hot water loads, currently <1% of the energy consumed in EU (Weiss and Biermayr, 2006) and US (Hudon et al., 2012) buildings is provided by solar. One impediment to greater market penetration is the high cost of systems (Hudon et al., 2012; Merrigan, 2007), particularly for moderate and cold climate regions. In the US, the cost to install a residential solar water heater capable of producing 190–380 L of hot water per day is

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Nomenclature

Latin symbols

a	radius of scattering domain (nm)
f_v	volume fraction of scattering domains (%)
I	radiative intensity (W m^{-2} sr^{-1})
L	material thickness (mm)
l_σ	path length travelled by ray (mm)
m	relative index of refraction
M	molar mass (kg mol^{-1})
$n_{particle}$	refractive index of scattering domains material
n_{matrix}	refractive index of matrix material
N	total number of rays used in Monte Carlo simulation
N_r	number of rays reflected
N_t	number of rays transmitted
Q_s	scattering efficiency factor
R	molar refractivity (cm^3 mol^{-1})
R_σ	random number used to determine the path length
R_θ	random number used to determine the scattering angle
R_ψ	random number used to determine the azimuth
$\hat{s}$	unit vector describing direction of ray
$\hat{s}_i$	unit vector describing direction of radiation before being scattered into $\hat{s}$
x	particle size parameter
z	direction of material thickness

Greek symbols

β	extinction coefficient (mm^{-1})
θ	scattering angle (radians)
λ	wavelength of incident radiation (nm)
ρ	density (kg m^{-3})
$\bar{\rho}$	slab reflectance (%)
σ_s	scattering coefficient (mm^{-1})
τ_L	overall optical thickness
$\bar{\tau}$	slab transmittance (%)
$\bar{\tau}_{solar}$	solar-weighted transmittance (%)
Φ	scattering phase function
ψ	azimuth angle (radians)
Ω	solid angle (sr)
ω	scattering albedo

reported to range from \$6000 to \$10,000 (Hudon et al., 2012). The National Renewable Energy Laboratory (NREL) predicts that if the cost could be lowered to \$1000–\$3000, without compromising durability or performance, solar water heaters would be at break-even cost with natural gas, and the market for solar thermal would be transformed (Hudon et al., 2012). The need to develop low-cost solar collectors is more acute for space heating, which requires larger collector areas.

One pathway to achieve significant cost savings is development of polymeric collectors suitable for all climate zones (Hudon et al., 2012; Köhl et al., 2012a; Rhodes, 2010; Tsilingiris, 1999). Currently, most of the solar thermal collectors intended for space heating and domestic hot water use copper absorbers with wavelength selective coatings and a low-iron glass cover. Polymeric collectors offer the potential to significantly reduce the installed cost (at least 50%) by reducing the material and manufacturing costs and by reducing the weight of the collector which in turn reduces the cost of installation (Burch et al., 2006; Hudon et al., 2012). Polymer collectors are the norm for pool heating, but unglazed and un-insulated pool collectors are not suitable for building applications in cool climates. One of the most relevant impediments to the development of glazed, polymer collectors is overheating of the absorber in the summer or during long dormant periods (e.g., when the homeowners are on vacation) (Hudon et al., 2012; Resch et al., 2009a; Resch and Wallner, 2009). The relative thermal index (UL746B, 1998) has been suggested as a recommended maximum service temperature for polymer absorbers (Raman et al., 2000). However, with relative thermal indices between 80 and 120 °C (Köhl et al., 2012b), the maximum service temperature of polymer absorbers can easily be exceeded under the conditions discussed. A low cost, passive overheat protection mechanism is needed to successfully launch glazed polymer collectors to the market.

Numerous approaches to overheat protection have been suggested for flat plate collectors. They can be divided into two broad categories: (1) those that increase thermal losses from the collector, and (2) those that decrease incident radiation at the absorber. Methods for increasing the thermal losses include various approaches to circulate cooling fluid through the collector (Baer, 1985; Buckley and Guldman, 1983; Harrison, 1979; Harrison and Cruickshank, 2012; Kusyy and Vajen, 2011; Laing, 1985; Palmatier, 1983; Wylie, 1993), venting (Harrison and Cruickshank, 2012; Kearney et al., 2005; Mahdjuri, 1999; Rich, 1995; Roberts et al., 2000; Russell and Guven, 1982; Scharfman, 1977; Scott, 1977), and evaporative cooling (Kearney et al., 2005). These methods often require additional hardware, active control, and increase parasitic energy. Venting is ineffective unless it can be implemented above and below the absorber plate (Kearney et al., 2005). However venting below the collector necessitates the removal of insulation which decreases collector performance during times when overheat protection is not needed. Venting may also introduce atmospheric contaminants and moisture into the