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A method for calculating the solar transmittance, absorptance and reflectance of a transparent insulation system

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Abstract

Transparent insulation materials (TIMs) can combine the advantages of opaque insulation with solar collection when applied to building facades. Mathematical models developed to calculate the optical performance of a transparent insulated (TI) system are presented. The TI-system modelled consisted of a 6 mm outer glass pane, a 22 mm wide polymethylmethacrylate (PMMA) capillary cell section and an 8 mm inner glass pane. When solar beam radiation passed through the TI-system, the solar transmittance, absorptance and reflectance that occurred in the system were calculated. Optical interactions at each layer in the TI-system were numerically modelled for five incidence angles. A direct to diffuse transmittance was calculated for solar radiation passing through the PMMA capillary cells with an incidence angle, θ_i, in excess of 0°. The calculated transmittance for the PMMA capillary cells at 0° incidence angle was 0.8264 with overall solar transmittance of up to 0.66 calculated for the whole TI-system, a value which is consistent with that found in previous research. This paper presents a method for calculating the optical properties for multiple PMMA capillary cells, encapsulated between two glass panes for different solar incidence angles, with input of relevant data from other sources. This method can also be adapted for other types of glazing systems.

Keywords: Solar transmittance; Solar absorptance; Solar reflectance; Optical properties; Transparent insulation materials; Numerical modelling

1. Introduction

Prior to the term ‘transparent insulation’ being introduced, in 1929, Russian researchers introduced a honeycomb made of paper between the glass cover and absorber plate in a flat-plate solar collector, to investigate the possibility of using low-conducting and solar absorbing walls as a thermal insulation material (Veinberg, 1959). This was followed by the use of glass tubes in a solar collector perpendicular to the absorber, which were designed to work at high absorber temperatures (Francia, 1961). A theoretical study of honeycomb structures between absorber and outer glass cover of a flat-plate solar collector was performed to suppress convective heat transport (Hollands, 1965). Until 1969, plastic honeycombs with desired thermal characteristics and transparency were still not available for flat-plate solar collectors (Tabor, 1969). The earliest TIMs were used as absorbers or convection suppression devices (CSDs) in solar collectors and it was not until the 1980s, TIMs were used for building retrofits for energy conservation.

In the last 30 years, theoretical and experimental studies were performed to improve suppression of natural convection using large-celled and small-celled honeycomb

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Nomenclature

A	aspect ratio	δ	thickness of capillary cell wall (m)
c_0, c_1	fit coefficients for honeycomb structure (cm^{-1})	L	thickness of glass pane (m)
d	hydraulic diameter (mm)	r	unpolarised solar radiation
D	thickness/length of capillary cell (m)	K^{-1}	inverse extinction coefficient (m)
f	first equation of series of equations		
j	difference of second over the first equation	*Subscripts*	
K	extinction coefficient (m^{-1})	i	incidence
n	number of cell walls that intersect with a light beam	ind	indefinite
$\dot{n}$	index of refraction	r	refraction
S_n	summation of 1st to nth equations	ou	outer
v	integer	$absorp$	absorptance
$Z_{1,2,\ldots,\ ind}$	coefficient	$reflect$	reflectance
ρ	solar reflectance (%)	cap	capillary cell
τ	solar transmittance (%)	k	KAPIPANE
α	solar absorptance (%)	in	inner
θ	solar incidence angle (°)	g	glass
ϕ	azimuth angle (°)	$\perp$	perpendicular
		II	parallel

structures. For examples, large-celled honeycomb structures made of highly transparent films, such as, fluorinated ethylene propylene (FEP), polypropylene, polycarbonate (PC) and fluorised films with U-values of approximately $2\ W/m^2\ K$ and working temperatures of between 60 °C and 100 °C were produced, commercialised, and used as CSDs for use in flat-plate collectors (Hollands et al., 1992; Platzer, 2001). Small-celled honeycomb structures made of glass or plastic, with square or circular cells, and improved optical and thermal properties (U-values of less than $1\ W/m^2\ K$), are easier to produce compared to large-celled honeycomb structures. The Fraunhofer Institute for Solar Energy System (FISES) had pioneered this area of research using different materials to suppress heat transfer by convection and radiation (Platzer, 2001). The small-celled honeycomb structures produced commercially are made of polymethylmethacrylate (PMMA), PC, acrylic translucent foam, and aerogels. Their optical and thermal performance are both influenced by the uniformity and quality of the cells produced. The development of these small-celled honeycomb structures for application to building façades, mostly in cold climatic regions to reduce building heating and lighting loads (Wong et al., 2007), enables the heat loss through building envelopes to be reduced, while keep the thickness of the building facades to a minimum. TIMs can be applied to building facades as TI-wall (wall) and TI-glazing (window) systems. A TI-glazing system is formed when a layer of TIM is encapsulated between two glass panels; whilst, a TI-wall system requires a massive wall to be in place behind a TI-glazing to provide thermal mass/storage. When used to replace standard opaque insulation materials, TI-systems not only perform similar functions to opaque insulation, such as, reduce heat losses and make indoor temperatures easier to control, the systems also allow solar transmittance of more than 50%.

Thermal and optical properties of TIMs made of different materials with different geometrical layouts have been determined theoretically, using mathematical models (Hollands, 1965; Hollands et al., 1978; Symons, 1982; Platzer, 1987; 1992a,b,c; Platzer and Kuehn, 1997; Arulanantham and Kaushika, 1994; Kaushika and Sumathy, 2003). The earliest theoretical model was developed to calculate angular dependent transmittance, $\tau(\theta)$, for a square honeycomb cell structure for various incidence angles, θ, taking into consideration cell thickness, depth and width (Hollands, 1965). Symons (1982) and Platzer (1987; 1992a,b) developed a more precise model derived from the summation of all individual rays transmitted or reflected at the cell walls to calculate $\tau(\theta)$, taking into consideration the average number of cell wall interactions for the incoming light beam, n, azimuth angle, ϕ, reflectance, ρ, and absorptance, α, at the cell wall. An approximate model was developed to determine parameters required to fit $\tau(\theta)$ for ten different types of honeycombs and capillaries, taking into consideration surface imperfections and bulk effects of the cells. The model was based on an idealisation and does not consider real factors in the measured data, which are deviations from the idealised model (Platzer, 1992b). The values of $\tau(\theta)$ calculated using different analytical models agreed well for most TIMs for smaller incidence angles (Wong et al., 2007), albeit only for a limited number of TIM samples (Platzer, 1992a,b).

Previous research has dealt with the calculation of optical properties for TIMs used in solar collectors. The development of TI-systems for building façade application, however, requires studies on whole systems, which include