Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 105 (2014) 58–70

SOLAR ENERGY

www.elsevier.com/locate/solener

Three dimensional heat transfer analysis of combined conduction and radiation in honeycomb transparent insulation

Hamdi Kessentini [a,b], Roser Capdevila [a], Jesus Castro [a], Assensi Oliva [a,*], Chiheb Bouden [b]

[a] *Heat and Mass Transfer Technological Center (CTTC), Universitat Politècnica de Catalunya-BarcelonaTech (UPC) ETSEIAT, Colom 11, 08222 Terrassa, Barcelona, Spain*

[b] *Université de Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis (ENIT), Laboratoire de Matériaux, Optimisation et Énergie pour la Durabilité (MOED), 1002 Tunis, Tunisia*

Received 12 December 2013; received in revised form 31 January 2014; accepted 17 February 2014
Available online 4 May 2014

Communicated by: Associate Editor Yanjun Dai

Abstract

In this work a three dimensional heat transfer analysis of honeycomb Transparent Insulation Materials (TIM) destined for improving the efficiency of flat plate solar collectors is performed. The cellular and repetitive nature of the TIM structure has allowed simplify the problem and simulate a single isolated cell with opaque and adiabatic walls. The combined heat transfer by radiation and conduction across the isolated cell is treated by means of the solution of the energy equation in its three dimensional form which is coupled to the Radiative Transfer Equation (RTE). The Finite Volume Method is used for the resolution of the RTE. The numerical results are compared to experimental measurements of the heat transfer coefficient on various honeycomb TIM given by different authors in the literature showing a reasonable agreement. The 3D simulations have allowed to study in detail the thermal behavior of the TIM and to understand the real physics of the problem. Finally, a parametric study is conducted in order to investigate the effect of the variation of the most relevant optical and dimensional parameters of the TIM on the heat transfer.

Keywords: Transparent insulation materials; Numerical simulation; Validation with experiments; Parametric study

1. Introduction

Transparent Insulation Materials (TIM) represent a class of thermal insulation that offer two major advantages: solar transparency and good thermal insulation. The applications of TIM spread throughout the wide field of passive solar thermal systems including building facades, space heating and day-lighting systems, integrated collector storage for domestic hot water supply, improved flat plate collectors (FPC).

The use of honeycomb TIM in solar collectors was pointed out first by Francia (1961) who used TIM made of glass tubes to reduce the thermal losses from the upper part of a FPC. Since the 1980s, TIM have received increasing attention with the intention of improving the efficiency of different solar thermal systems (Hollands and Iynkaran, 1985; Goetzberger and Rommel, 1987; Schmidt et al., 1988; Schmidt and Goetzberger, 1990; Braun et al., 1992; Hollands et al., 1992; Avanti et al., 1996; Kaushika and Reddy, 1999; Faggembauu et al., 2003a,b; Kaushika and Sumathy, 2003; Wong et al., 2007; Kumar and Rosen, 2011). TIM have also been used in many studies with the aim of developing high efficiency FPC (Platzer, 1992a,b,c; Rommel and Wagner, 1992; Goetzberger et al., 1992;

* Corresponding author. Tel.: +34 93 739 8192; fax: +34 93 739 8101.
E-mail address: cttc@cttc.upc.edu (A. Oliva).

http://dx.doi.org/10.1016/j.solener.2014.02.027
0038-092X/

Nomenclature

A	TIM aspect ratio
D	equivalent diameter of the TIM (m)
d	wall thickness (m)
f_s	fraction of the reflectivity which is specular; $f_s = \rho_w^s/(\rho_w^s + \rho_w^d)$
g	gravitational acceleration (m s^{-2})
G	incident radiation (W m^{-2})
I	radiation intensity (W m^{-2} sr^{-1})
I_b	black body intensity (W m^{-2} sr^{-1})
L	cell height (m)
M_w	number of discrete solid angles
Nu	Nusselt number; $Nu = \dot{q}_f L/\lambda(T_{ho} - T_{co})$
$\vec{n}$	unit surface normal vector
$N_x,\ N_y,\ N_z$	number of control volumes in x, y and z directions
$N_\theta,\ N_\varphi$	number of control angles in the polar and azimuthal directions
$\dot{q}_f$	convective heat transfer across honeycomb (W m^{-2})
$\dot{q}$	heat flux (W m^{-2})
$\dot{q}_R$	net radiative heat flux (W m^{-2}); $\vec{\dot{q}}_R \cdot \vec{n} = \int_{4\pi} I(\vec{n}\cdot\vec{s})d\Omega$
Ra	Rayleigh number; $Ra = g\tilde{\beta}(T_{ho} - T_{co})L^3/\nu\alpha$
S_m	modified source function
S_{TIM}	cross-sectional area of hexagonal honeycomb cell (m^2)
$\vec{s}$	unit direction vector
T	temperature (K)
$X,\ Y,\ Z$	dimensionless Cartesian coordinates
$x,\ y,\ z$	Cartesian coordinates

Greek symbols

α	thermal diffusivity of fluid (m^2 s^{-1})
ϵ	emissivity
ρ	reflectivity
θ	polar angle (rad)
θ_i	angle of inclination face horizontal (rad)
φ	azimuthal angle (rad)
κ	absorption coefficient (m^{-1})
σ_s	scattering coefficient (m^{-1})
β	extinction coefficient (m^{-1})
$\tilde{\beta}$	thermal expansion coefficient (K^{-1})
β_m	modified extinction coefficient (m^{-1})
Ω	solid angle (sr)
Φ	scattering phase function
λ	thermal conductivity (W m^{-1} K^{-1})
δ	discrepancy
ν	kinematic viscosity of fluid (m^2 s^{-1})

Subscripts

b	black body
c	conduction
co	cold
d	diffuse
exp	experimental
e, w, n, s	east, west, north and south
g	gas
ho	hot
i	control volume index
num	numerical
P	central node
r	radiation
s	specular
t	total
TIM	Transparent Insulation Materials
w	wall

Superscripts

d	diffuse
l	discrete direction
s	specular

Schweiger, 1997). In the majority of these works, TIM were made of glass capillary tubes due to their good resistance to high temperatures. However, they need to be embedded in a double glazing unit for mechanical purposes leading to a significant increase in both the weight and manufacturing cost of the FPC. Plastic TIM were also proposed for FPC (Rommel and Wagner, 1992; Abdullah et al., 2003; Suehrcke et al., 2004; Ghoneim, 2005) due to their lower cost and weight. The main drawback of plastic TIM is their limitation for resisting the high stagnation temperature that this type of FPC could reach, especially in hot summer periods. Recently, Kessentini et al. (2011) used plastic TIM as a cover for a FPC with an overheating protection system for protecting the TIM from stagnation conditions. The presented results showed the ability to make the FPC with TIM a commercial product destined for industrial applications that need heat at low-to-medium temperature level such as in food and textile industry, solar drying of wood, crops and fruits, or in solar cooling and air conditioning systems. FPC with plastic TIM using heat pipe as passive overheating protection system have been also recently introduced to the market showing good thermal performances (TIGI LTD, 2011; Adel, 2013). Moreover, Giovanetti et al. (2011) presented new types of cellulose triacetate honeycomb TIM also destined for the use in improved FPC. These recent interests of using plastic TIM in FPC with overheating protection systems have generated the interest in performing the present study.

In FPC, TIM has been used to reduce convective and radiative heat losses. The TIM layer reduces the convection