Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 105 (2014) 290–302

SOLAR ENERGY

www.elsevier.com/locate/solener

Analysis of a hybrid solar window for building integration

Tejas Ulavi [a], Tim Hebrink [b], Jane H. Davidson [a,*]

[a] Department of Mechanical Engineering, University of Minnesota, 111 Church St. S.E., Minneapolis, MN 55455, USA

[b] 3M Corporate Research Process Lab, 3M Center, 208-01-01, Maplewood, MN 55144, USA

Received 21 August 2013; received in revised form 11 January 2014; accepted 8 March 2014
Available online 6 May 2014

Communicated by: Associate Editor Ursula Eicker

Abstract

The technical performance of a hybrid 'solar window' that provides heating in addition to daylighting is evaluated. A wavelength selective film is coupled with a compound parabolic concentrator (CPC) to reflect and concentrate the infrared portion of the solar spectrum onto a tubular absorber while transmitting the visible portion of the spectrum into the interior space. The optical performance of the CPC/selective film is predicted using a Monte Carlo Ray-Tracing model. An adaptive concentrator geometry based on asymmetrical truncation of CPCs is analyzed for vertical windows and horizontal skylights. The predicted visible transmittance is 0.66–0.73 for single glazed windows and 0.61–0.67 for double glazed windows. The solar heat gain coefficient and the U-factor are comparable to existing glazing technology. The annual thermal efficiency for double glazed windows/skylights based on use in Minneapolis, MN is 24–26%.

Keywords: Hybrid; Solar window; Wavelength selective film; Building integration

1. Introduction

Daylighting is widely recognized as a key strategy towards an aesthetically pleasing and energy efficient built environment. Several studies link human health and productivity to natural light (Kim and Kim, 2010; Plympton et al., 2000; Vandewalle et al., 2006). Daylight produces a true color rendering, provides visual comfort, and is considered to be a major cue to the human circadian rhythm (Gochenour and Andersen, 2009). With appropriate lighting control systems, daylighting can reduce electrical energy consumption by more than 30% (Chow et al., 2013; Li et al., 2006). As highly glazed commercial buildings are synonymous with modern architectural design, the development of energy efficient commercial glazing technologies is important.

Modern glazing technologies offer various approaches to regulate their thermal and optical performance. Multi-layer glazing separated by air, vacuum, inert gas or transparent insulators such as silica aerogel (Buratti and Moretti, 2012) reduce thermal losses. Tinted or reflective glazing technologies (Chow et al., 2010; Mohelnikova, 2009; Alvarez et al., 2013), low emissivity coatings (Alvarez et al., 2013; Martin-Palma, 2009) and spectrally selective glazing (Alvarez et al., 2013; Martin-Palma, 2009; Xu et al., 2006) regulate the spectral response of the window. Switchable glazing technologies such as electrochromic (Page et al., 2007; Piccolo et al., 2009; Granqvist et al., 2010), thermochromic (Granqvist et al., 2010; Mlyuka et al., 2009) or photochromic glazing and liquid crystals (Gardiner et al., 2009) have been developed as part of 'smart' fenestration systems to provide varying levels of daylighting and passive thermal control for the interior.

An attractive approach for glazing systems is to harness the sunlight not utilized for daylighting to generate

* Corresponding author. Tel.: +1 (612) 626 9850.
E-mail address: jhd@me.umn.edu (J.H. Davidson).

http://dx.doi.org/10.1016/j.solener.2014.03.006
0038-092X/

Nomenclature

A	area (m^2)
C	geometric concentration factor
c_p	specific heat capacity at constant pressure (J/kg K)
D	tube diameter (m)
F_R	heat removal rate
G	incident solar irradiance (W/m^2)
g	fraction of incident solar radiation
h	heat transfer coefficient (W/m^2 K)
H	depth of the CPC (m)
L	length of CPC reflector (m)
$\dot{m}$	mass flow rate (kg/s m^2)
N	number of rays
n	number of concentrators/absorber tubes in the collector
R	random number, uniformly distributed in (0, 1)
Q_u	useful energy (W/m^2) (3600 J/m^2 for hourly data)
$\vec{r}$	direction of incident radiation
S	energy absorbed per unit absorber area (W/m^2) (3600 J/m^2 for hourly data)
$SHGC$	solar heat gain coefficient
T	temperature (K)
U	net heat transfer coefficient between two surfaces (W/m^2 K)
U-factor	net transmittance through the window (W/m^2 K)
U_L	overall loss coefficient (W/m^2 K)
$V(\lambda)$	CIE photopic luminosity function
v_w	wind velocity (m/s)
W	width of the CPC (m)
x, y, z	Cartesian coordinates

Greek symbols

α	absorptance of the absorber tube
β	PV cell temperature coefficient (°C^{-1})
γ	PV cell irradiance coefficient
ε	emittance
η	efficiency
θ	incidence angle (°)
θ_c	nominal half-acceptance angle (°)
θ_{d1}, θ_{d2}	truncated half-acceptance angle (°)
λ	wavelength (nm)
ρ	reflectance
σ	Stefan–Boltzmann constant (J/s m^2 K); standard deviation
τ	transmittance
τ_{vis}	visible transmittance

Subscripts

a	absorber tube; absorbed rays
b	beam radiation
c	CPC glass cover; convection
c_2	additional CPC glass cover
cd	conduction
$cell$	PV cell
d	diffuse radiation
e	effective value
fi, fo	fluid inlet, outlet
i	incident rays
in	interior
m	wavelength selective film
$\hat{n}$	normal (to a surface)
r	radiation
$\vec{r}$	directional
s	specular reflection
t	transmitted rays
th	thermal module
xy, yz	planes
∞	ambient
λ	spectral

Superscripts

DL	daylit space
T	thermal module

alternate forms of energy to supplement the overall sustainability of the built structure. Semi-transparent building integrated photovoltaic (BIPV) glazing (Chow et al., 2010; Li et al., 2009) can be used to offset interior lighting loads, but suffer from low transmittance in the visible. Chow et al. (2010, 2011) analyzed water-flow double-pane window. Water is circulated through the cavity of a double glazed window to reduce solar heat gains by 32% as compared to a double glazed window with absorptive and clear glass, in addition to annual heat extraction by water that was equal to the annual solar heat gain through the double glazed window. Davidsson et al. (2010) proposed and tested a multifunctional, window integrated PV/T with tiltable aluminum reflectors to concentrate incident solar energy. The electrical and thermal performance of the window was comparable to roof-integrated PV and solar thermal collectors of the same area. A drawback of the design is that in the active mode, the window acts more like a wall due to the opaque concentrators.

In the present work, a hybrid ‘solar window’ based on the principle of spectral band splitting is proposed and analyzed. The proposed device performs multiple functions: it daylights the interior space; it generates useful thermal energy which can be used to offset domestic hot water or space heating loads; and it can be used to regulate heat gains through the window. Fig. 1 shows the design concept and an illustration of the window in a building. As shown in Fig. 1(a), a wavelength selective film is attached to a