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Smart windows: Thermal modelling and evaluation

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Abstract

A numerical investigation of the performance of a multi paned smart window integrated with water-cooled high efficiency third generation GaAsP/InGaAs QWSC (~32% efficiency) solar cells illuminated by two-axis tracking solar concentrators at 500× in the inter pane space is presented. Optimising system parameters such as optical concentration ratio and coolant (water) flow rate is essential in order to avoid degradation in system performance due to high cell temperatures and thermal stresses. Detailed modelling of the thermo-fluid characteristics of the smart windows system was undertaken using a finite volume CFD package. Results of this analysis which considered the conductive, convective and radiative heat exchange processes taking place in the interior of the smart window system as well as the heat exchange to the internal and external ambient environment are presented.

Keywords: Smart windows; Photovoltaic; Facades; CFD

1. Introduction

Solar energy is increasingly being recognised as one of the main substitutes for fossil fuels due to its essentially non-polluting inexhaustible nature. Photovoltaic/thermal (PV/T) solar collectors, first proposed by (Kern and Russell, 1978), yield a higher utilisable energy output per unit collector area (Tripanagnostopoulos et al., 2007; Vats and Tiwari, 2012). The approach of combining a thermal and PV component is considered more appropriate for concentrating solar systems in which heat removal from the PV cells will be a critical issue.

Currently different types of double-skin façades are employed in buildings to provide increased thermal comfort while lowering space heating and cooling energy consumption (Safer et al., 2005a). Solar radiation is comprised of both long and short wave radiation, i.e., heat and light. When seeking to regulate the amount of solar radiation entering into a building, the challenge is to achieve desired levels of daylight intensity without excess introduction of the concomitant heat. Excessive direct solar insolation in the interior space, workplace or home, can lead to discomfort due to high levels of glare when the sun is directly in the field of view or is specularly reflected from indoor surfaces (Kim et al., 2009; Piccolo and Simone, 2009) and should be avoided. Blinds are frequently used within such façades to control the intensity of the incident direct solar radiation component by

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Nomenclature

D_h	depth of horizontal window segment (m)
D_v	depth of vertical window segment (m)
D_{vc}	depth of the differentially heated vertical cavity (m)
d_e	external tube diameter (m)
d_i	internal tube diameter (m)
H_h	height of horizontal window segment (m)
H_v	height of vertical window segment (m)
H_{vc}	height of the differentially heated vertical cavity (m)
h_{cback}	heat transfer coefficient of back window pane ($Wm^{-2}\,K^{-1}$)
h_{ccell}	heat transfer coefficient of solar cell ($Wm^{-2}\,K^{-1}$)
h_{cfront}	heat transfer coefficient of front window pane ($Wm^{-2}\,K^{-1}$)
h_{clens}	heat transfer coefficient of Fresnel lens ($Wm^{-2}\,K^{-1}$)
h_{ctube}	tube-air heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
h_{cwater}	water-tube heat transfer coefficient ($Wm^{-2}\,K^{-1}$)
W_h	width of horizontal window segment (m)
W_v	width of vertical window segment (m)
X	optical concentration ratio

Greek symbols

η_{cell}	solar cell electrical efficiency
μ_τ	turbulent viscosity (Pa s)
ρ_{cell}	solar cell reflectivity
ρ_g	reflectivity of window pane
ρ_{lens}	reflectivity of Fresnel lens
ρ_{tube}	reflectivity of copper tube
τ_{cell}	solar cell transmissivity
τ_g	transmissivity of window pane
τ_{lens}	transmissivity of Fresnel lens
τ_{tube}	transmissivity of copper tube

blocking the radiation from entering the building and thus reducing the cooling loads. However, these do not use the intercepted solar energy. A smart window, illustrated in Fig. 1, aims to control and regulate solar energy influx through such double skin façades to the interior of buildings. Glass coated with thin films that can change their optical properties reversibly from transparent to opaque when heated and cooled (Bange, 1999), or when subject to an applied electrical current are of great interest (DeForest et al., 2013), again however they do not utilise the incident solar energy for electricity production.

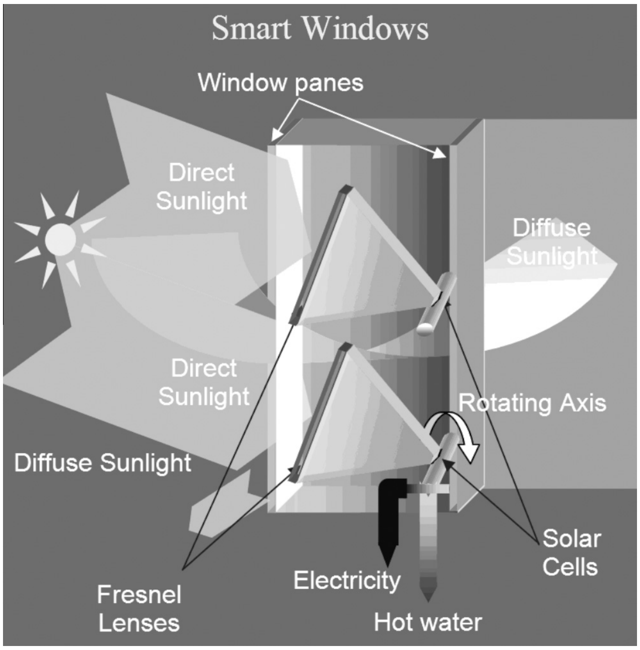

Fig. 1. A conceptual arrangement of a smart window showing its operation.

We examine a new concept of smart windows whereby water cooled concentrator-PV cell units are incorporated inside the gap between two panes of a double glazed window. Two-axis tracking Fresnel lens concentrators coupled to actively cooled high efficiency PV cells have been simulated.

Optical concentration ratio is defined as the ratio between the aperture area to the collector area, while the effective concentration ratio is calculated taking into account the reflection from both aperture and collector surfaces. PV cells considered in this study are the Quantum Well (QW) square solar cells, having area of 16 mm^2 which were reported to achieve efficiency of ~32% under an effective concentration ratio of 500× (Adams et al., 2011; Rohr et al., 2006). The variation of the cell efficiency with concentration ratio is shown in Fig. 2.

When incorporated into a double skin building façade, a point focus or linear Fresnel lens will separate the direct (beam) solar radiation from the diffuse component and concentrate the former on the solar cell whilst facilitating the passage of diffuse radiation into the interior of buildings. Such multifunctional smart windows are able to (i) generate electricity, (ii) block direct sunlight with consequent reduction in building energy cooling load, (iii) transmit diffuse sunlight to provide natural daylight and (iv) provide domestic hot water.

The following system parameters need to be optimised to achieve maximum thermal, optical and electrical performance:

- The optical concentration ratio that provides the best solar to electrical conversion efficiency of the solar cell, taking into account the reduction in performance that results from increased operating temperature.