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A thermal model of hybrid cooling systems for building integrated semitransparent photovoltaic thermal system

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ABSTRACT

In today's world, most buildings are dependent on artificial cooling and artificial lighting, thus, increasing electrical consumption. This increases the emission of greenhouse gases which leads to environmental degradation. To reduce the dependence on the electrical grid and reduce the energy consumption for cooling the buildings, there is a need to apply passive and/or hybrid cooling systems to maintain the indoor thermal conditions. Evaporative cooling, ventilation, daylighting are examples of such systems. The paper makes an attempt to develop a thermal model of passive cooling systems (evaporative cooling, natural ventilation, daylight and heat storage capacity of materials) for building integrated semitransparent photovoltaic thermal systems and discusses their relevance in present day scenario. These concepts are effective in controlling the indoor room temperature by 30.16 °C decrease. The day light at the same time also helps enhance human performance. Impact of packing factor on room air temperature, solar cell temperature, floor temperature, solar cell efficiency and daylight savings has also been studied.

1. Introduction

Present day architecture can be termed anemic to outside environment, completely sealed and isolated from the outside climate, to provide comfortable indoor conditions. This leads to huge energy consumption as it necessitates dependence on mechanical devices for heating and cooling all year round irrespective of the conditions prevalent outside. Solar irradiation being all pervasive leaves no structure untouched necessitating the continuous March for reducing power consumption in line with thermal needs. An estimated 40% of the worldwide energy consumed is used for thermal management of buildings (W.B.C.f.S. Development, 2009).

Passive cooling (PC) plays a vital role in the sustainable development of the buildings. PC technique means prevention and modulation of heat gain and heat dissipation. Therefore, it is important to wisely choose the fenestration arrangement, thermal mass or insulating material to reduce the indoor heat gain and provide a comfortable indoor thermal environment. It is estimated that the average cooling demand for the residential and commercial sector might increase by 750% and 275% respectively by 2050 (Santamouris, 2016). Passive and/or hybrid cooling systems should be used to increase electrical efficiency in the maintenance of comfortable indoor thermal conditions. Evaporative cooling (EC), natural ventilation (NV), daylight (DL) are examples for such systems.

1.1. Evaporative cooling (EC)

Hot ambient air is allowed to pass over a damped surface before its introduction to the interior spaces. The hot ambient air is cooled using the evaporation of water and is circulated within the premises. This is the oldest technique used in the form of dessert coolers in arid areas (ambient temperature ranging between 37 and 42 °C) and is highly efficient but is limited by the increase in indoor humidity. Water is sprayed on the roof and the ceiling cools the room beneath by convection and radiation. This process is called passive evaporative cooling. Chungloo and Limmeechokchai (2007a) studied passive EC in the hot and humid climate of Thailand, and summarized that passive EC is also effective in reducing room temperatures for metal ceilings.

Natural ventilation is the most effective passive cooling technique. Wind towers are the simplest solution to enhance the

Abbreviations: BiSPVT, building integrated semitransparent photovoltaic thermal; PC, passive cooling; EC, evaporative cooling; DL, daylight; NV, natural ventilation.

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Nomenclature

A	area [m^2]
b	breadth of the roof [m]
C_a	specific heat of air [J/kg K]
c_w	specific heat of water [J/kg K]
$Ex_{sun,daylight}$	rate of exergy of solar energy through non-packing area of PV module [W]
h_c	convective heat transfer coefficient [W/m^2 K]
h_{cr}	convective heat transfer coefficient to room [W/m^2 K]
h_i	inside heat transfer coefficient [W/m^2 K]
I(t)	solar intensity [W/m^2]
k	thermal conductivity [W/m K]
L	length of the roof [m]
L_g	thickness of glass [m]
M_a	mass of air [kg]
$\dot{m}_{ew}$	rate of water consumption [kg h^{-1}]
$\dot{m}_w$	mass flow rate of water [kg/s]
N	number of air changes [–]
P	partial pressure [N/m^2]
T	temperature [°C]
$\acute{T}$	temperature (without water flow) [°C]
$\bar{T}$	average temperature [°C]
T_0	temperature below the room under study [°C]
T_{ref}	reference temperature [°C]
T_s	sun surface temperature [K]
U_{tcw}	overall heat transfer coefficient from solar cell to water [W/m^2 K]
v	velocity of air [m/s]
V	volume of room [m^3]
η_c	solar cell efficiency [%]

Greek symbols

α	absorptivity [–]
β	packing factor [–]
β_0	temperature coefficient [$°C^{-1}$]
η_0	electrical efficiency at standard test condition [–]
γ	relative humidity [%]
τ	transmissivity [–]
λ	latent heat of water [J/kg]

Subscripts

a	ambient air
c	solar cell
f	floor of room
g	glass of solar cell PV module
m	PV module
R	roof
r	room
w	water

natural flow of air within the premises by receiving the outdoor air at the top and circulating the same in the interiors via openings at the bottom. A major limitation to the cooling efficiency of a wind tower is the climate and location. Qingyuan and Yu (2014) concluded that the effectiveness of EC depends on the difference between humidity ratio of outdoor air and wet bulb temperature at saturation.

1.2. Natural ventilation (NV)

Fenestrations (windows and openings) are the most important elements of buildings in terms of comfort and energy use per unit area (Bessoudoa et al., 2010) and are the major contributors to the solar heat gain of the interiors. Thus shading devices are common strategies to prevent the same. These fenestrations are deliberately installed to provide fresh air, oxygen, extract indoor pollutants, odor in order to maintain a good standard of air quality with minimum capital cost and environmental loss (Liping and Hien, 2007). NV in form of air movement and cross ventilation is the most important element for passive cooling design since it not only increases the evaporation rate but also increases the rate by which the warm indoor air is replaced by the cool outdoor breeze. Location and orientation of windows and doors have a significant influence on the NV. Zoning of the buildings in grid iron pattern, spaced approximately six times their height results in proper wind movement with a uniform flow and removal of stagnant zones. Flourentzou et al. (1998) studied the measurements of velocity and discharge coefficients in already constructed buildings and introduced the concept of neutral pressure level. The proposed models provided useful information for the architects regarding cooling and NV. A simplified method to save cooling load using PC systems based on ventilation (direct night ventilation, air-soil heat exchangers, controlled thermal phase-shifting, EC, and their combinations) was developed by Campaniço et al. (2014). Faggianelli et al. (2014) reviewed various ways of natural cross ventilation in a building for Mediterranean coastal zones.

*Various configurations of window openings are seen in vernacular architecture to enhance the velocity of air. Some of them include small window on huge wall, tapered window with smaller inside section. Domed spaces with vents near the ceilings were often used so that the hot air rises and vents out from the openings near the ceilings. The various studies on NV in brief have been summarized in Table 2 with remarks.

1.3. Daylight (DL)

Sustainable techniques used for cooling of the building by natural means are called passive cooling techniques. Thus, any system which reduces the dependence on mechanical air conditioning and cooling load of the building is a part of PC. Introduction of DL in the interiors reduces the dependence on artificial lighting. The cooling demand of the building is also reduced by minimizing the use of artificial lighting as a direct consequence of the reduced heat losses. Therefore, DL is an efficient PC concept which reduces the cooling load and enhances efficiency. Consideration of sun path and wind direction for room orientation is very important for DL and ventilation. Lighting constitutes about 14%, 26% and 31% share of the total electrical consumption in Europe, U.S and Spain in non-residential buildings respectively (Zinzi and Mangione, 2015). Artificial lighting constitutes about 19% of the electrical consumption worldwide (Gago et al., 2015). Parise and Martirano (2013) developed a criterion to evaluate the annual DL impact on the energy performance on internal lighting based on the availability of natural light. 30–77% reduction in energy consumption of buildings can be achieved by using daylight strategies for various combinations of building geometry, window sizes and glazing types (Pyonchan Ihm and Krarti, 2009). DL strategies are dependent on architectural characteristics like form, aesthetics and functionality. Moreover, DL also has positive psychological effect on human behavior and performance (Loisos, 1999).

Integrating the building with Semitransparent Photovoltaic (SPV) with façade Didoné and Wagner, 2013; Ng and Mithraratne,