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Effect of packing factor on the performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system with air duct

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ABSTRACT

In this paper, an attempt has been made to study the effect of packing factor of semitransparent photovoltaic (PV) module integrated to the roof of a building, on the module and room air temperature, and electrical efficiency of PV module. Energy and exergy analysis have been carried out by considering different packing factors (0.42, 0.62, and 0.83) of PV module namely mono crystalline silicon (m-Si), poly crystalline silicon (p-Si), amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and a heterojunction with thin layer (HIT). It is observed that the decrease in the temperature of PV module due to decrease in packing factor, increases its electrical efficiency. It is also found that the decrease in packing factor increases the room temperature. Maximum annual electrical and thermal energy is found to be 813 kWh in HIT and 79 kWh in a-Si PV module respectively with packing factor of 0.62.

1. Introduction

One of the promising applications of photovoltaic (PV) technologies is building integrated photovoltaic thermal (BIPVT) system. It provides electricity, space heating and day lighting by the use of semitransparent PV modules. In such systems, no additional land area is required. It avoids the cost of batteries remarkably when grid connected [1] and also reduces costs and losses associated with transmission and distribution [2]. The above properties and applications provide the scope of research and study in the field of BIPVT system. Mei et al. [3] carried out experimental work to determine the potential for high temperature operation in BIPV roof system. He suggested that the temperature rise in BIPV roof system is problematic if back ventilation is restricted. Lu and Yang [4] studied the sustainability of roof mounted BIPV system of 22 kW by comparing its energy payback time and greenhouse gas payback time. He further concluded that the system is green with a life span of 20–30 years. Chen et al. [5] found that there are thermal energy outputs of 8.5–10 kW from a BIPVT roof with surface area of 64 m^2. Semitransparent PV modules in a building saves annual electricity of 1203 MWh, was reported by Li et al. [6]. A semitransparent photovoltaic heat gain model for calculating the heat gain was developed by Fung and Yang [7]. Anderson et al. [8] concluded that thermal efficiency decreases by decreasing the roof inclination of BIPVT system. Song et al. [9] suggested that the PV modules installed at 30 °C performed better than vertical PV module in terms of annual power output. An experimental work on three configurations of BIPVT system integrated to roof was carried out by Pantic et al. [10]. In his work, he concluded that forced circulation of air increases the thermal efficiency.

In earlier studies, mono crystalline, poly crystalline silicon (m-or p-Si) and amorphous silicon (a-Si) modules, inclination of PV modules, weather conditions and natural and forced circulation of heat transfer have been considered by various researchers. However the effect of packing factor and other PV technologies (cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and heterojunction with thin layer (HIT) [11,12]) on the BIPVT system have not been taken into account. It is important to observe the effect of packing factor on the temperature and efficiency of PV module. In m-Si and p-Si, packing factor of a PV module can be varied by varying the area of PV cells for a given area of PV module, which has been shown in Fig. 1(a) and (b). In Fig. 1(a), there are 36 cells, each having an area of 0.0139 m^2 for a given area of PV module. On the other side, in Fig. 1 (b), each cell area is half of 0.0139 m^2 for the same area of PV module and therefore, increases the non packing area i.e. decreases packing factor. However, in case of thin film PV, the packing factor can be varied according to the design e.g. as per need the area of thin filmed PV and glass can be arranged in an alternate fashion to allow solar radiation to pass through the glass area, as shown in Fig. 1(c). Therefore, in this paper, energy and exergy analysis have been evaluated for a building integrated semitransparent photovoltaic thermal (BISPVT) system, installed on the roof of a room with air duct, for different types of PV modules with different packing factors.

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Nomenclature

A	area (m^2)
B	breadth of wall (m)
b	width of PV module (m)
C	specific heat of air ($J\,kg^{-1}\,K^{-1}$)
H	height of wall (m)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{p1}, h_{p2}	penalty factors due to glass cover and PV module (dimensionless)
$I(t)$	incident solar radiation ($W\,m^{-2}$)
K	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length (m)
L_1	length of PV module (m)
M_a	mass of air (kg)
$\dot{m}$	mass flow rate of air ($kg\,s^{-1}$)
N	number of air change per hour
N_1	number of sunshine hours per day
P_r	Prandtl number (dimensionless)
R_e	Reynolds number (dimensionless)
T	temperature (°C)
$U_{tc,a}$	overall heat transfer coefficient from solar cell to ambient through glass cover ($W\,m^{-2}\,K^{-1}$)
$U_{Tc,f}$	overall heat transfer coefficient from solar cell to flowing air through glass cover ($W\,m^{-2}\,K^{-1}$)
$U_{p,r}$	overall heat transfer coefficient from brick and insulation to room air ($W\,m^{-2}\,K^{-1}$)
$(UA)_t$	overall heat transfer coefficient from room to ambient air through walls and windows ($W\,K^{-1}$)
V	volume of a room (m^3)
V_a, v_a	air velocity ($m\,s^{-1}$)
Greek symbols	
α	absorptivity (dimensionless)
β	packing factor (dimensionless)
τ	transmissivity (dimensionless)
$(\alpha\tau)_{eff}$	product of effective absorptivity and transmissivity
ρ	density ($kg\,m^{-3}$)
ν	kinematic viscosity ($m^2\,s^{-1}$)
η	efficiency (dimensionless)
Subscripts	
a	ambient air
b	brick
c	solar cell
cm	sand, cement and polystyrene (insulation)
eff	effective
el	electrical
f	fluid (air)
f_i	inlet fluid
f_o	outgoing fluid
m	module
n_o	number of walls
ov	overall
PVroof	roof of PV modules
p	insulated roof or insulated wall (brick and insulation material)
r	room
s	straw fibre (insulation)
th	thermal

2. Problem identification

Eight different ways of installing the PV modules on a building have been studied by Vats and Tiwari [17]. The maximum room temperature has been obtained in the semitransparent PV modules integrated to the roof of a room (without duct). Integration of the PV modules, without duct, is preferred for newer construction(s) for day lighting in addition to the electrical and thermal energy. PV modules with air duct can be used on any existing building for indirect heating. Hence the proposed design is an alterative option for the development and installation of the PV modules.

3. Working principle

The cross section view of BISPVT system integrated to the roof of a room with air duct is shown in Fig. 2. In this figure the semitransparent PV modules are installed at angle of 34° to the horizontal which corresponds to latitude of the Srinagar, India. The PV modules are located outside the room and sealed from all the sides. Inlet and outlet vents are provided on the roof for the air flow. When solar radiation falls on the PV module, it gets heated. The room air enters through inlet vent, takes the heat of PV module and escapes through outlet vent. The hot air at outlet enters into the room and replaces the cooler room air. For smooth circulation of air fan is provided but not shown in figure. In this way thermal energy of PV modules is utilized for space heating. Further this reduces the temperature of PV module and increases the electrical efficiency. In the study 9 PV modules are considered and each has 1 m length and 0.61 m breadth. A room with dimensions of 3 m × 1.81 m × 4 m and PV roof area of 5.44 m^2 has been considered for the present study. Mass flow rate of 0.85 $kg\,s^{-1}$ through air duct has also been considered. The room is insulated by the layer of sand, cement, polystyrene and straw fibre.

4. Thermal modelling

The following assumptions have been made to write the energy balance equation of a BISPVT system integrated to the roof with air duct:

1. One dimensional heat conduction in quasi-steady state is considered.
2. There is no temperature stratification in the air of a room due to force mode of operation.
3. The room is thermally insulated and physical properties of air are constant.

4.1. Analytical expression for temperature of semitransparent PV module and room air

Following Vats and Tiwari [17], the expression for solar cell temperature of semitransparent PV module is given by

$$T_c = \frac{(\alpha\tau)_{1eff} I(t) + U_{tc,a} T_a + U_{Tc,f} T_f}{U_{tc,a} + U_{Tc,f}} \tag{1}$$

where,

$$(\alpha\tau)_{1eff} = \tau_g \alpha_c \beta_c - \eta_{PV,m}$$

Temperature of PV module indirectly depends upon the transmissivity of glass (τ) absorptivity of cell (α), packing factor (β) and efficiency (η) of module through $(\alpha\tau)_{1eff}$.