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An investigation on energy performance assessment of a photovoltaic solar wall under buoyancy-induced and fan-assisted ventilation system

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HIGHLIGHTS

- Novel testing of a PV solar wall with ventilation through an outdoor test-room.
- Energy performance comparison under buoyancy-induced and fan-assisted ventilation.
- A simplified energy performance model of a PV solar wall and its validation.

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ABSTRACT

The aim of this paper is to present an investigation on energy performance assessment of a photovoltaic solar wall with an operation of either buoyancy-induced or fan-assisted ventilation system. The vertical photovoltaic solar wall was installed on façade of a prefabricated outdoor test-room located at Concordia University, Montréal, Québec, Canada. The experimental apparatus of the photovoltaic solar wall was a built construction with two commercially available photovoltaic modules, an air cavity and an insulated back layer. The selected operating conditions for the ventilated PV facade were utilized for establishing their electrical and thermal characteristics. Measurements of electric power, outlet air velocities, temperatures, solar intensities and thermal time constant were obtained from the experiments. The maximum combined electrical plus thermal efficiencies obtained after analysis of the presented measurement data were 31.4% and 37.6% for buoyancy-induced and fan-assisted based air ventilation respectively. The energy balance performed for buoyancy-induced and fan-assisted ventilation demonstrated that operation of fan-assisted ventilation achieved better performance, due to considerable gain in enthalpy of air by convection heat loss. A simplified energy performance model is proposed and validated. The agreement between predictions of the proposed energy performance model and measurement results is presented to be very good.

1. Introduction

Recent years have seen a significant improvement in design configurations and enhancement in the energy efficiency of photovoltaic-thermal systems. For application in buildings, a photovoltaic-thermal system can be used as an integrated architectural element as well as a mechanical and electrical component of building services system. Its successful integration into the building design depends upon the close association as well as cooperation of the concept designer, mechanical and electrical systems designers, general construction contractor and each of the specialized Building Integrated Photovoltaic-Thermal (BIPV/T) system and façade contractors who may install portion of the mechanical and electrical systems of integrated Building Integrated Photovoltaic (BIPV) system. To be successful, all stakeholders involved in the project must be familiar with the design requirements of applied energy systems. Each should at least be familiar with the basic design procedures used, flexibilities in BIPV/T system, space required and time at which such work must be done so that it is fully coordinated and managed. Because all of these people are involved and because the mechanical system must fit into the construction of the BIPV/T system, it is important that the entire construction team be familiar with applied energy system and its principles of design. However, some major hurdles towards adoption of BIPV/T technology are: (i) thermal system integration issues and contest with solar-thermal technology for its thermal applications in buildings; (ii) periodical cleaning and removal of dust and snow from BIPV panels; (iii) defective quality due to competitive price scenario in market; (iv) unreliability of

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Nomenclature

General

Δy	distance between discretized surface nodes in y direction (m)
A_n	face area of photovoltaic solar wall {H X W} (m^2)
C_n	specific heat at constant pressure (J kg^{-1} K^{-1})
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
H	height of photovoltaic solar wall (m)
h_b	convective heat transfer coefficient for insulation panel (W m^{-2} K^{-1})
h_p	convective heat transfer coefficient for PV module (W m^{-2} K^{-1})
hr_b	linearized radiation heat transfer factor (W m^{-2} K^{-1})
hr_p	linearized radiation heat transfer factor (W m^{-2} K^{-1})
i	generated D.C. current from the photovoltaic solar wall (Amperes)
k	variation of y-ordinate from 0 to (n − 1)
k_b	thermal conductivity of the back panel (W m^{-1} K^{-1})
k_p	thermal conductivity of the PV module (W m^{-1} K^{-1})
L	air gap width in solar wall (m)
m	mass flow rate through the solar wall (kg s^{-1})
n	number of discretized elements in y-ordinate
N	total number of nodes in the grid
S	solar intensity on the photovoltaic solar wall (W m^{-2})
T_a	temperature variable for the air (°C)
T_b	temperature variable for the insulation panel (°C)
t_b	thickness of the insulation panel (m)
T_p	temperature variable for the PV module (°C)
t_p	thickness of PV module (m)
R_p	connected resistance of rheostat across the series connection of PV modules (Ohms)
T_s	building space temperature (°C)
v	air velocity near the outlet of the photovoltaic solar wall (m/s)
V_p	total potential difference across the rheostat with series connection of PV modules (Volts)
V_r	potential difference across the rheostat's resistance converted to electric power (Volts)
W	width of photovoltaic solar wall (m)

Greek letters

α	short-wave absorbtion of the solar irradiation on PV module
ρ_n	density (kg m^{-3})
$(\tau\alpha)_e$	effective transmittance-absorbtance product for PV module
ψ	constant for steady mass flow conditions
$\eta_{pv\text{-}T}$	overall performance rating of solar wall (%)
η_T	thermal efficiency of solar wall (%)

Subscripts

a	air motion through the photovoltaic solar wall
o	ambient air
b	back panel
p	PV module
r	resistance
pv-T	combined electric and thermal power
s	building space
T	thermal

photovoltaic modules; and (v) mismatch between useful life span of building integrated photovoltaic modules and architectural elements like façade and glazing.

Passing air from behind of photovoltaic (PV) panels is utilized to achieve their cooling. With the result, there is a decrease of temperature of PV cell and its components. The air in effect gets heated while passing through the cooling duct. Cooling is achieved by means of both natural convection and forced convection. The typical value of temperature coefficient for crystalline silicon solar cell is approximately −0.45% per °C [1]. In a comparative analysis, it was found that for the case of forced convection there is no decrease of efficiency as cell temperature was always found below Nominal Operating Cell Temperature (NOCT), while in case of natural convection, the efficiency decreases to 8.9% from 11.8%, because of high-rise in PV cell temperatures [1]. The PV cell temperatures in the case of natural convection reached up to 51 °C, with outside air temperature of −5 °C, while in the case of forced convection, the temperatures up to 20 °C were achieved, under similar environmental conditions [1]. Increase in the operational efficiency of the PV panel is achieved by recovering this heated air from the rear cooling ducts of the PV panels [1].

In a photovoltaic solar wall, photovoltaic and solar-thermal technologies are combined together through integration into the façade [1–5]. The main advantages of photovoltaic solar wall are: (i) combined heat and power generation; (ii) waste heat-recovery as well as energy use near its point of generation; (iii) minimization of delay time, costs and energy losses, due to heat-generation, transmission and distribution from outdoor duct into the indoor environment in comparison with the roof-top inclined systems; (iv) increase in thermal resistance of the building façade; (v) protection from the excessive heating at high solar intensities by passing and controlling the amount of heat transport with use of fan pressure; (vi) daylighting through the glazed section with semi-transparent PV modules; and (vii) with air as fluid medium, ventilation in the form of pre-conditioning of fresh air into the building.

The aim of this paper is to present an investigation of a photovoltaic solar wall with ambient still air as fluid for transporting heat into the built environment. The energy performance assessment of a photovoltaic solar wall is conducted under buoyancy-induced ventilation and fan-assisted ventilation. This paper comprises of (i) a system design analysis of the experimental setup; (ii) an experimental testing through measurements; (iii) a simplified energy performance assessment model; (iv) an energy performance assessment of buoyancy-induced and fan-assisted ventilation; and (v) model validation through experimental results. The schematic sketch for experimental apparatus consisting of a photovoltaic solar wall is illustrated in Fig. 1(a)–(e). A quasi-steady-state energy performance analysis is conducted on the photovoltaic solar wall to represent the critical case of combined electric and enthalpy gain of air with limited solar energy availability.

The photovoltaic solar wall system was rectangular in cross-sectional area with an air-gap length, L between the PV module and the insulation panel. As illustrated in Fig. 1(c), the photovoltaic solar wall was composed of two commercially available PV modules and an insulated panel with induced air movement through the photovoltaic solar wall from the inlet damper system. The air-passage was assumed to be heated with constant and uniform quasi-steady-state solar heat flux, q_p dissipated from the PV modules. The insulation panel was constituted as part of the spandrel of the façade of an outdoor room as illustrated in Fig. 1(c). The ambient air was moving into the photovoltaic solar wall through air ventilation created either through buoyancy-induced or fan-assisted pressure. The fan pressure was created by operation of