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Study of a thermoelectric air duct system assisted by photovoltaic wall for space cooling in tropical climate

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ABSTRACT

The integration of building structure with renewable components such as photovoltaic (PV) panel and thermoelectric modules (TEMs), provides new opportunities for exploiting natural energy and minimizing impact on the environment. This paper presents experimental and simulation investigation of a novel thermoelectric air duct system (TE-AD) assisted with photovoltaic (PV) system for space cooling in Malaysian weather condition. The north facing TE-AD system consist of fifteen TEMs assisted by 300 Wp south wall facing PV system for cooling of test room whose volume is 9.45 m^3. Both simulation and experimental results were in good agreement and showed that PV assisted TE - AD system when operated at 6 A gives the optimum temperature difference of 6.8 °C with cooling capacity of 517.24 W and COP of 1.15. Combination of the TE-AD and PV system saves 1806.75 kWh/year with an additional benefit of Freon free, highly reliable and less fossil fuel consuming system.

1. Introduction

With the increment in human population in the course of recent hundreds of years and estimated that would reach 9.6 billion by 2050 [1], there has been a massive increase in demand of the housing sector. Located in central South-East Asia, Malaysia is a fast growing country having a tropical climate with the daytime temperatures of 29–34 °C, relative humidity of 70–90% and monthly solar radiation of around 400–600 MJ/m^2, all over the year. So, for providing comfort condition to the occupants, building sector of Malaysia utilizes high energy intensive mechanical cooling system which increases energy consumption by 34% from the year 2005–2010 [2]. This problem becomes more awful when channeling of conditioned air via an air duct losses 25–40% of energy. Thus, researchers start searching alternative of an air conditioning system, which rely less on refrigerants, compressor, evaporator and grid connected power supply. Placement of Photovoltaic panel (PV) over the exterior part of the building has been studied by Yang et al. [3] and found that about 33–50% of the cooling load of the building was reduced by integrating PV cladding on the wall. Brinkworth et al. [4] theoretically and experimentally analyze the impact of ventilated air duct on the performance of PV claddings mounted on the wall/roof and found that the peak outside surface temperature of the wall was reduced by 20 °C as compared to a normal wall. Sun et al. [5] investigated the effect of building orientation, inclination, shading-type (Building integrated photovoltaic system) BIPV claddings on the PV module output and cooling load reduction of building for Hong Kong climate. The simulation results showed that during summer time BIPV claddings can reduce the cooling load by 51.6% and 43.2% for windows and concrete walls respectively, with maximum electricity generation per unit PV area of 76.8 kW h/m^2 at a tilt angle of 10°. Sun et al. [6] compares the efficiency of classic Trombe wall with PV assisted Trombe wall both through experiment and simulation. The study revealed that installing PV panels of dimension 0.83 m wide and 2.6 m tall over the glazing of classic Trombe wall reduces the thermal performance of the Trombe wall system by 17%. This reduction was due to the obstructed penetration of the sun's rays into the mass wall [6]. Peng et al. [7] examined the annual thermal performance of a PV-W and the normal wall for Hong Kong climate. The result shows that during summer PV-W reduces 2.9 °C indoor temperature and about 50% heat gain rate

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Nomenclature

A_{PV}	area of photovoltaic cell, (m^2)
A_{Glass}	area of photovoltaic glazing, (m^2)
C_f	friction factor along the air duct
C_g	specific heat of glass, (J/kg K)
C_P	specific heat of air, (J/kg K)
C_w	specific heat of wall, (J/kg K)
COP	coefficient of performance
d	hydraulic diameter of air duct, (m)
D	depth of air duct, (m)
E	electric power rate generated by PV cells, (W/m^2)
g	gravitational acceleration, $g = 9.8066$, (m/s^2)
G	total solar radiation on the vertical plane, (W/m^2)
h_{co}, h_{ci}	convective heat transfer coefficients on the outside and inside surface of PV glass panel, (W/m^2 K)
h_{nrwo}	radiation heat transfer coefficient on the outside surface of normal wall, (W/m^2 K)
h_{nwi}, h_{nwo}	convective heat transfer coefficient on the inside and outside surface of normal wall, (W/m^2 K)
h_{ro}, h_{ri}	radiation heat transfer coefficients on the outside and inside surface of PV glass panel, (W/m^2 K)
h_{rwo}	radiation heat transfer coefficient on the outside surface of PV wall, (W/m^2 K)
h_{wo}, h_{wi}	convection heat transfer coefficients on the outside and inside surface of PV wall, (W/m^2 K)
L	height of PV wall, (m)
L_{room}	depth of room, (m)
$\dot{m}$	mass flow rate, (kg/s)
T_{cold}	cold side temperature, (K)
TEM	thermoelectric module
TE-AD	thermoelectric air duct system
T_{hot}	hot side temperature, (K)
T_a	ambient temperature at the next time step, (K)
T_{in}	indoor room temperature at the next time step (K)
T_{nwo}, T_{nwi}	temperature of outside and inside surface of normal wall, (K)
T_o	air duct outlet temperature at the next time step (K)
T_P, T_e	temperature of PV glass panel and air duct, (K)
T_w	temperature of PV wall, (K)
T_{wo}, T_{wi}	temperature of outside and inside surface of PV wall, (K)
T_{SKY}	sky temperature at the next time step, (K)
T_a	ambient temperature at the next time step, (K)
T_{in}	indoor room temperature at the next time step, (K)
T_o	air duct outlet temperature at the next time step, (K)
V_a	velocity of the air flow in the duct, (m/s)
w	width of PV wall, (m)
w_{room}	width of the room, (m)
ρ	humidity ratio at the next time step
ε	ratio of PV cell coverage
ξ_1,ξ_2,ξ_3	emissivity factors
$\lambda_a,\lambda_g,\lambda_w$	thermal conductivity of air, glass, wall, (W/m K)
ρ,ρ_g,ρ_w	density of air, glass, wall, (kg/m^3)
α_{pv}, α_{wall}, α_{nwall}	absorptivity of the PV cells, PV wall and the normal wall
α_{wpv}, α_{npv}	equivalent absorptivities of the elements with and without PV cell on the glass panel
τ_{pv},τ	transmissivity of the PV cell's outside layers, the elements without PV cell on the glass panel
β	heat expansion coefficient, (K^{-1})

as compared to the normal wall while in the winter PV wall reduces 32% of heat loss and 69% of heat gain as compared with the normal wall. Peng et al. [8] compares the thermal and power performance of photovoltaic double-skin façade (PV-DSF) under three different testing conditions i.e. ventilated, buoyancy-driven ventilated and non-ventilated. The result shows that the ventilated PV-DSF gives 3% and 1.9% higher energy output as compared to non-ventilated and buoyancy-driven ventilated PV-DSF system with additional benefits of lower operative temperature and higher heat gain reduction. Recently, Peng et al. [9] developed a simulation model on Energy Plus to analyze the annual overall energy performance of a ventilated PV-DSF for the Mediterranean climate. Finding of this research recommend that for optimum performance of PV-DSF, thickness of air gap should lie in the range of 400 and 600 mm. Naturally-ventilated PV-DSF saves about 35% of electricity consumption per year with 65 kW h/m^2 yearly electricity production in Berkeley.

But for the tropical region where both temperature and humidity remain high throughout the year, BIPV alone cannot provide thermal load reduction inside the buildings. So, in this study implementation of the thermoelectric module (TEMs) along with a PV system was investigated for the development of self-sustainable air conditioning system. Thermoelectric coolers (TEC) are solid semiconductor material which works on the principle of Peltier effect [10], with the benefits of refrigerant free, convenient installation, no moving parts and reliable operation [11].

Application of solar thermoelectric technology in a building can be broadly classified into two categories, i.e. Active building envelope system (ABE) and solar TE refrigeration and air conditioning system. Khire et al. [12] developed an active building wall system (ABW) by integrating TEMs and PV system. This system actively controls the heat flux through the wall and reduce the cooling load of the building. Liu et al. [13] developed a novel solar thermoelectric radiant wall (ASTRW) system. Results show that the overall efficiency of ASTRW system after incorporating passive heat losses was about 1.9% and 5.5% respectively. A novel solar thermoelectric cooled ceiling combined with displacement ventilation system (STCC-DV) was proposed by Liu et al. [14]. The result shows that in cooling mode COP and the total heat flux reaches to 0.9 and 60 W/m^2 when operated at 5 V. While in heating mode, the total heat flux and COP reaches to 110 W/m^2 and 1.9 when operated at 4 V. Dai et al. [15] experimentally investigated solar powered TE refrigeration system and obtained the relationship between the intensity of solar radiation and coefficient of performance (COP) of a TE refrigerator. Result shows that COP of 0.3 and temperature range of 5–10 °C at refrigerated space was achieved. Abdul-Wahab et al. [16] designed and experimentally tested portable solar TE cooler. The result shows that in approximately 44 min the temperature of the refrigeration was reduced from 27 to 5 °C with a COP of 0.16. Cheng et al. [17] tested a solar-driven TEMS with a waste heat regeneration unit for green building applications. For enclosure of dimension $30 \times 12 \times 10$ cm^3 temperature difference between inside and outside can reached to 16.2 °C in cooling mode. He et al. [18] examined the effect of solar assisted TE heating and cooling system implemented in a room of volume 0.125 m^3. The results show that the COP of 0.45 and minimum temperature of 17 °C was achieved with thermal efficiency of 12.06%. This system can also raise the temperature of the stored water in a tank of capacity 18.5 L by