Performance evaluation of PV-Trombe wall for sustainable building development

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Abstract

This paper presents a detailed simulation model of a single room building integrated with PV Trombe wall (PV-TW). Performance is evaluated in terms of room temperature, cooling load and PV efficiency by varying the air flow velocity for three different PV-TW Glazing types (i.e. Single Glazing, Double glazing, Double glazing filled with gas (Argon)). Simulation was done on TRNSYS software having inputs parameters as climatic conditions, building construction details, thermal properties of materials, detail of PV-TW and orientation of the building were inserted. By varying the air flow velocity and comparing the results of all three types of glazing it was found that PV Double glazing filled with argon shows significant results in reduction of cooling load of building, mean air duct temperature. Reduction of mean air duct temperature results in lowering of PV cell temperature which enhances the efficiency of PV panel. Also maximum room temperature reduction was found while using a double glass filled with argon PV-TW, which further reduces thermal load of the building. Air flow velocity shows significant effect on the performance of PV-TW up to certain values after which its effect stagnates and no further improvement was shown in all three types of PV-TW.

Keywords: Photo Voltaic Trombe wall; Glazing type; Room Temperature; PV efficiency; Air flow velocity

1. Introduction

Buildings and structures are the fundamental desideratum of mankind, which provides not only shelter but additionally safety and security from weather and other things. Among the all energy utilizer sectors such as conveyance, Industry, agriculture, energy and waste management, the building sector alone consumes around 40% of all engendered energy [1]. Building energy utilization is therefore the key issues to address in order to meet the climate change challenges [2].

Nomenclature

| Symbol | Description                                        |
|--------|---------------------------------------------------|
| A<sub>pv</sub> | Area of PV cell                     |
| A<sub>gl</sub> | Area of PV-Glazing                     |
| A<sub>s</sub> | Cross-sectional area normal to the height of the air duct (m<sup>2</sup>) |
| C<sub>g</sub>, C<sub>p</sub> | Specific heat capacity of glass, wall (J/kgK) |
| d | Air duct hydraulic diameter (m) |
| D | Depth of air duct (m) |
| E | Electric power rate generated by PV cells (W/m<sup>2</sup>) |
| G | Total solar radiation (W/m<sup>2</sup>) |
| L | Height of PV-TW (m) |
| h<sub>co</sub>, h<sub>ci</sub> | Convection heat transfer coefficients on the outside surface and inside surface of PV glass panel (W/m<sup>2</sup>K) |
| h<sub>ro</sub>, h<sub>ri</sub> | Radiation heat transfer coefficients on the outside surface and inside surface of PV glass panel (W/m<sup>2</sup>K) |
| h<sub>n</sub>, h<sub>n</sub> | Convection heat transfer coefficients on the outside surface and inside surface of PV-TW glass panel (W/m<sup>2</sup>K) |
| T<sub>pv</sub>, T<sub>a</sub>, T<sub>e</sub>, T<sub>o</sub> | Temperature PV glass panel, ambient, air duct (°C) |
| T<sub>w</sub> | Temperature of PV-TW wall (°C) |
| T<sub>n</sub>, T<sub>n</sub> | Temperature of outside and inside surface of... |
PV-TW wall (°C)

| Symbol | Description          |
|--------|----------------------|
| ΔP     | pressure head        |
| V_a    | velocity of the airflow in the duct (m/s) |

Greek symbols

| Symbol | Description          |
|--------|----------------------|
| ρ     | density of the air, glass, respectively (kg/m3) |
| λ_g   | thermal conductivity of glass (W/mK) |
| ξ_1, ξ_2 | emissivity factors |
| β     | heat expansion coefficient (K⁻¹) |
| ε     | ratio of PV cell coverage |
| η     | electrical efficiency |

For the tropical countries such as Malaysia green construction has therefore become a flagship of sustainable development in this century, which not only reduces operating costs, but withal increases occupant productivity, organizational marketability and provides a positive impact on public health and the environment[3]. 9th Malaysian plan therefore gives much accentuation on Solar passive systems that utilizes solar energy to heat, cool, ventilate or light buildings, without the desideratum of electricity or mechanical instruments [4]. Most typical solar passive systems used nowadays is Trombe walls [5]. A sun-facing wall disserevered by glass and an air space from the outdoors climate, absorbs solar energy and discharge it selectively towards the interior at night is kenned as Trombe wall. By affixing photovoltaic (PV) cells on the cover glazing a novel Trombe structure known as a PV-TW was designed by Ji et al. [6] that use solar energy not only for heating and cooling purposes but withal to engender electricity by photovoltaic cells. There are various accessories on which efficiency of PV-TW depends such as Vents, Wall Insulation and fans. In this study by varying air flow velocity performance of PV-TW was studied for different type of glazing (i.e. Single glass, Double glass and Double glass filled with Argon PV panel).

2. Methodology

2.1. Description of the experimental house

Computer simulation using TRNSYS software was conducted using the single-room house facility with PV Trombe wall located at the campus of Universiti Teknologi PETRONAS (4°23'11"N and 100°58'47"E, Perak, Malaysia) as shown in Fig 1. All dimensions of the test cell were taken from the previous studies which is 3.0 m (width, X) X 3.0 m (depth, Y) X 2.6 m (height, Z) [7, 8]. All external walls was made of three layer consisting 20 cm thick brick wall and cement plaster on the both side of walls . The plaster thickness was 1.8 cm for outside layer and 1.3 cm for inside layer. Roof was also made up into  three-layer consisting insdie layer of limestone tile (16 cm thick), middle layer of cement mortar (2.2 cm thick) and outermost layer of cement plaster (2.3 cm thick). The ground was made of first layer of cement mortar (12 cm thick), second layer of sand gravel (22 cm thick) and the last layer of soil or mud phuska (35 cm thick). Window on the north- west wall having dimensions of height (0.314m) and width (0.23 m). Window was made of plywood of thickness 2.5 cm. The windows open inside and having no overhangs. A single steel door is on the south-east wall of dimensions (2.134 m) height and (0.914 m) width. The door was made of 0.5 cm thick GI metal sheet. The door opens inside. The PV-TW on the south or sun facing wall, consists of a PV glass panel with an area of 2.64 m (height) X 0.84 m (width) and a thickness of 5 mm, a matt ebony painted wall and an air duct with a thickness of 0.16 m in between.

![Schematic diagram of the test room with PV Trombe wall (All dimensions are in meter)](image)

The outer glazing of the PVTW is 5 mm thick glass, on the back of which is affixed with 5 cm X5 cm commercial polycrystalline silicon PV cells with grid distribution. The PV glazing then appears of a series colour of dark blue with a packing factor of PV cells as 0.332. The outer glazing of the PVTW is 5 mm thick glass, on the back of which is affixed with 5 cm X5 cm commercial polycrystalline silicon PV cells with grid distribution.

The PV glazing then appears of a series color of dark blue with a packing factor of PV cells as 0.332. A vents of the size of 0.4 m (X) X 0.15 m (Z) are opened at the lower part of the absorber wall to provide passage for the air flow between the room and the air duct. One vent is 0.15 m above wall foundation and another vent is 0.15 m below roof level. The distance between vents is kept 2.3 m.

2.2. Numerical Modelling

The ratio of PV cell coverage is defined as [9]

\[
\text{ε}_e = \frac{A_{PV}}{A_{Glass}}. \tag{1}
\]

By neglecting the heat capacity of PV cells because of its thickness, the energy balance equation of the PV glass panel is established according to [9,10].

\[
\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + b \tag{2}
\]

where,
\[ b = \frac{(S_c + S_p) T_r}{\delta} \]

\[ S_r = \frac{\xi_h h_{ir} + h_{ir}^2 + \xi h_{ir}^2}{2} \]

\[ E = G \eta (1 - 0.0045(T_{pv} - 298.15)) \]

\[ \eta \] is the electrical efficiency at standard conditions 14%.

The energy balance along the vertical direction, \( X \), inside an air duct can be given as:

\[ \frac{DC_p}{dx} \frac{dT}{dT} = h_1(T_{in} - T_{o}) - h_2(T_1 - T_2) - \rho V_c DC_p \frac{dT}{dx} \]

The velocity of air flow in the air duct \( V_a \) can be calculated as follows [11]

\[ V_a = \sqrt{\frac{0.5XgB(T_{in} - T_{o})L + (\Delta P / \rho)}{C_f (L/d) + (C_\infty A_1^2 / A_2^2) + (C_{out} A_1^2 / A_2^2)}} \]

2.3. Building Simulation

The first step in establishing a simulation predicated optimization control, is computing a dynamic model that virtually performs as an authentic building. Therefore, dynamic simulation software was needed with the ability to compute the thermal behaviour of the building, with a degree of flexibility and user-graphically interface. For this reason, TRNSYS (TRaNsient SYstem Simulation Program) v.17 [12] was utilized. The TRNSYS software utilizes a transfer function method for simulation of the building. The model was built up starting from the case study and then transmuting parameters to elongate the results. PV-TW was simulated transmuting air flow rate inside the duct of PV-TW with different glazing type (single glazed, evacuated double glazed and Double-glazing filled with gas). Once the model was calibrated, it was possible to postulate the results running for a whole year.

The entire model structure done inside the TRNSYS environment where it was defined by 9 modules (Types). (Type 9a) data reader was installed to read the authentic weather data which was engendered as a .txt file. This data consists of the ambient temperature, irradiation and the relative sultriness that was accumulated from the weather station. (Type 567-2) was installed in connection with (Type 36) and then to (Type 56). This component was intended to model a glazed solar collector which has the dual purport of engendering power from embedded photovoltaic (PV) cells and providing heat to an air stream passing beneath the absorbing PV surface. (Type 36d) was intended to model a thermal storage wall is essentially a high capacitance solar collector directly coupled to the room. Absorbed solar energy can transfer inside the room by one of the two paths. One passage is convected through the inside wall surface, the energy is then convected and radiated into the room. The second path is convection from the sweltering external wall surface to air in the gap. Room air permeating the gap is heated, carrying energy into the room. The wall also loses energy through the glazing by conduction, convection and radiation to the environment. (Type 25) is intended to model a thermal deportment of a building having multiple thermal zones. (Type 25) is a printer component used to output (or print) culled system variables at designated intervals of time. (Type 642) models a fan that is utilized to vary the air flow velocity.

3. Results and discussion

In order to investigate the thermal and electrical performance of Photo Voltaic Trombe wall having different glass properties, a simulation program is written in TRNSYS v 17. Air flow velocity is varied and their effect on various parameters has been discuss below, also ambient conditions during the day were presented in Fig 2.

![Figure 2. Ambient condition as function of time.](image)

3.1. Effect variation of air flow velocity with room temperature for different type PV-TW

Effect of Single glass, Double glass and Double glass filled with Argon PV-TW on room temperature by varying air flow velocity were shown in Fig. 3, 4 and 5. It was found that Double glass filled with Argon PV-TW shows maximum room temperature reduction. Also, it was found that as the air flow velocity increase room temperature decreases as more heat is taken away by air this is in agreement with the results published by other researchers [11, 13]. After reaching a certain value of air flow velocity which is 2.0 m/s effect of air flow on the performance of PV-TW stagnates and no further reduction in room temperature is shown in all the three cases.
3.2. Effect variation of air flow velocity with PV efficiency for different type PV-TW

Effect of Single glass, Double glass and Double glass filled with Argon PV-TW on PV efficiency by varying the air flow velocity were shown in Fig. 6, 7 and 8. It was found that maximum PV efficiency was achieved in the case of Double glass filled with Argon PV-TW. Also, it was found that as the air flow velocity increase PV efficiency increases as more heat is taken away by the air which further reduces PV cell temperature and enhanced the efficiency of PV-TW.

This was in agreement with the results published by other researchers [14, 15,16] and also proved from EQ 2 that maximum power output decreases linearly with rise in PV cell temperature. It was also found that after reaching a certain value of air flow velocity which is 1.75 m/s effect of air flow
on the performance of PV-TW stagnates and no further improvement was shown in all the three cases.

![Figure 8: Variation of PV efficiency with air flow velocity for double glass filled with argon PV-TW](image)

3.3. Effect variation of air flow velocity on cooling load for different type PV-TW

Effect of Single glass, Double glass and Double glass filled with Argon PV-TW on cooling load by varying the air flow velocity were shown in Fig. 9, 10 and 11. It was found that cooling load in all the three cases, first decrease and then increases and finally decreases in the night time. This behavior is due to heat wave propagation from outside surface which is PV panel to inner surface of wall which requires time or called as time lag [17].

![Figure 9. Variation of cooling load with air flow velocity for Single glass PV-TW](image)

![Figure 10. Variation of cooling load with air flow velocity for double glass PV-TW](image)

![Figure 11. Variation of cooling load with air flow velocity for double glass filled with argon PV-TW](image)

The simulated results shows that among all the three cases Double glass filled with argon PV-TW shows highest reduction in cooling load at air flow velocity of 1.75 m/s. Double glass PV-TW also shows significant reduction in cooling load but about 18% less than Double glass filled with argon PV-TW.

By comparing the cooling load characteristics of single glass, double glass and Double glass filled with argon PV-TW it was found that ventilated double glass filled with argon provide more insulation towards heat penetration. So the amount of heat penetrated inside the building and at the back portion of PV panel get reduce. Also it was found that after reaching a certain value of air flow velocity which is 1.75 m/s effect of air flow on the cooling load of stagnates and no further improvement was shown in all the three cases. Other
researchers also found that ventilated PV-TW has significant effect on cooling load of building [18,19,20].

4. Conclusions

Simulation study was performed to examine the effect of changing air flow velocity on room temperature, cooling load and PV efficiency of PV panels for three types of PV-TW (i.e. Single, Double and Double glass filled with argon). It was found that Double glass filled with argon PV-TW shows significant results in term of temperature and cooling load reduction and PV efficiency increment. Also, it was found that the effect of air flow velocity becomes stagnant after attaining certain value which is 1.75 m/s. The present study suggested that double glass filled with argon and double glass PV-TW at air flow velocity 1.5 m/s is preferable over the single glass PV-TW and can provide feasible solutions for high energy consumption and environmental degradation especially for tropical region.

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