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The performance comparison of fan-assisted Trombe wall system

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Abstract:
One of the various systems used for energy conservation in buildings is building integrated photovoltaic (BIPV) Trombe wall system. This system is applied to the blind south facades of buildings to produce heat and electrical energy. In this paper, the energy performance comparison of fan-assisted single glass, double glass and a-Si semi-transparent PV module integrated on the Trombe wall façade of a model test room built in Izmir, Turkey has been carried out. The system has been operated during 19 - 21 January. The temperature variations at certain nodes where the temperature probes are placed have been evaluated. The measured values of inter-space, inlet and outlet air temperatures for single glass, double glass and photovoltaic module have been compared. The surface temperatures of the photovoltaic module and the thermal wall have also been evaluated. The comparison of the thermal performance for three modules has been made according to the experimental results. The change in electrical efficiency by surface temperature of the photovoltaic module has also been interpreted. According to the experimental results 10% of solar radiation has been transmitted through the semi-transparent photovoltaic module. Meanwhile, the electrical efficiency of PV cells can reach 4.5 % according to the experimental results.

Keywords: *Forced convection, BIPV Trombe wall system, thermal storage, electrical efficiency, electric output.*

1. Introduction

The energy demand of the world has grown rapidly over the past few decades. The total energy demand had reached 12.0 billion tones of oil equivalent (toe) that is 3.2 times the level in 1965 (3.8 billion toe) (Sheng, Y., Shi, X. & Zhang, D., 2012). The increase in the use of fossil origin fuels causes environmental pollution and troubles in ecological cycles. The energy used for heating, cooling and climatization of buildings should be minimized with some design based precautions. Special systems like Trombe wall system might be used to decrease energy consumption in buildings (Yilmaz, Z., Kundakci, B., 2008).

Trombe wall system uses solar energy to heat, ventilate and provide thermal comfort in buildings (Zamora, B., Kaiser, A., 2009). Solar radiation passes through the glass, is absorbed by the thermal wall and is converted into energy. The energy is stored during the day and is released to the interior of the thermal wall by conduction and convection at night (Agrawal, B., Tiwari, G.N., 2011). The heat stored in the thermal wall is released to the interior of the room gradually by convection and radiation to provide thermal comfort the occupants require. Two vents are placed on the upper and lower parts of the thermal wall that lets the hot air into the room and remove the cold air from the room. This air flow occurs by convection due to the buoyancy effect. PV/T collectors aim to increase electrical efficiency of the PV cells by cooling the PV module surface (Aste, N., Chiesa, G., Verri, F., 2008). BIPV Trombe wall is a novel version where the glazing in classic Trombe wall is replaced by a PV module. In other words, BIPV Trombe wall is a combination of these two systems used both for producing electricity and heat simultaneously for energy savings. Besides, the dark-blue color of PV cells makes the building more appealing (Sun, W., Ji, J., Luo, C., He, W., 2011). In BIPV Trombe wall, the cool air in the room enters the inter-space through the lower vent, absorbs the waste heat behind the PV panels, becomes hot and enters the room through the upper vent. The absorption of PV heat results in the increase in PV efficiency as the PV panels function better when they are cool (Chow, T.T., Hand, J. W., Strachan, P. A., 2003). Free air convective cooling is a simple and low cost method of keeping electrical efficiency at an acceptable level (Hegazy, A.A., 2000). It is an energy efficient system that is easy to apply on south facing facades of both existing and new buildings.

BIPV/T systems turned out to be an attractive technology in the late 1990s. Either semi-transparent or opaque type photovoltaic modules can be used in BIPV/T systems. The semi-transparent type systems are integrated with the walls, roofs and windows of the building using day lighting, while the opaque type systems and the semi-transparent type systems without lighting can be integrated with the walls and roofs of the building (Agrawal, B., Tiwari, G.N., 2010).

Trombe wall has been used in decades as an efficient solar heating method. There is a massive thermal wall and a clear glazing cover with an air duct in between. As the surface of the thermal wall is painted in black, it is hard to meet the aesthetical requirement of buildings. PV cells integrated on the cover glazing of Trombe wall are more appealing. PV Trombe wall convert solar radiation into electricity and heat simultaneously (Sun, W., Ji, J., Luo, C., He, W., 2011).

The studies on conventional Trombe walls have been made intensively in the past decades. Borgers and Akbari (1984) modeled the channel between two parallel plates in Finite Difference Method. They obtained the flow and temperature profiles between the plates and presented the change in the total flow rate on the flow characteristics. Sparrow and Azevedo (1985) studied the effect of channel width on natural convection between vertical parallel plates. They concluded that to avoid flow blockage effects, the channel width should be greater than 4,7cm. Sandberg and Mashfegh (1996a) made experiments of fluid flow and heat transfer in a vertical channel heated from one side by PV elements. They made the numerical analysis for steady-state two-dimensional model (Sandberg, M., Moshfegh, B., 1996b). They concluded that the flow rate through the channel increased with increasing channel width. This was attributed to the decreasing wall frictional resistance with increasing channel width.

Mei et al. (2003) carried out dynamic thermal simulation of a building with an integrated ventilated PV façade with TRNSYS. They concluded that the cooling loads are marginally higher with PV façade for locations studied, whereas the heating loads depend critically on location.

Chow et al. (2003) studied the application of a large-scale building-integrated PV technology on a 30-storey hotel building in China. They concluded that different design options exhibit short-term electrical performance differences, but have similar long-term electrical yields.

Ji et al. (2008) studied two identical test rooms with and without PV-TW experimentally and theoretically. The influence of PV-TW on thermal environment of the test room has been investigated under different operating conditions. It was concluded that the maximum indoor temperature of the PV-TW was found to be 5-7°C higher in winter compared to the reference room. Bloem (2008) designated the electrical and thermal performances of BIPV/T system based on experimental results. Different photovoltaic modules have been used to seek the effect of photovoltaic design to electrical performance. Thus, he concluded that an experimental outdoor set-up for BIPV applications is necessary to develop a calculation model.

Fung and Yang (2008) developed one-dimensional transient simulation model for semi-transparent BIPV module. They studied the effects of different parameters. The results show that the most important component of heat gain is solar radiation. Anderson et al. (2009) made the theoretical analysis via the use of a modified Hottel-Whillier model for opaque type PV module roof application. Insulating the rear of BIPV/T may be irrelevant for the roof applications when the system is installed on an enclosed air filled attic. Therefore, they presented that integrating the BIPV/T into the building rather than onto the building results in a lower cost. Cheng et al. (2009) developed a correlation between the optimal angle of the BIPV system and the latitude of the system's site. The system is supposed to be integrated on south oriented tilted roof at 20 different locations in the Northern Hemisphere. Therefore, it was concluded that to get maximum solar radiation in northern hemisphere, the system should face south and the angle of the panel should be equal to the latitude of the terrain. Trinuruk et al. (2009) compared 2 estimation models used most commonly for predicting PV module temperatures in BIPV/T application for tropical climatic conditions of Thailand. They found that both models are strongly over-biased in temperature predictions. Agrawal and Tiwari (2010) developed one-dimensional transient model to designate the most suitable BIPV/T system for climatic conditions of India. The results show that when the mass flow rate of air is constant, the system connected in series gives a better performance. When the velocity of air flow is constant, the system connected in parallel gives a better performance. Sun et al. (2011) carried out experimental and numerical studies to investigate the performance of the PVTW with different south façade designs. They developed a dynamic numerical model to integrate the vented PVTW with indoor environment. Thus, they concluded that in the design of south façade integrated with PVTW, the dynamic coupling among PVTW, window and indoor air must be taken into account. Kundakci Koyunbaba et al. (2011) developed a two dimensional CFD model under transient conditions for BIPV Trombe wall

Figure 1. *The interior view of the test room.*

system. They validated the simulation model by comparing the simulation results with the experimental ones. Kundakci Koyunbaba et al. (2012) developed two-dimensional CFD models under transient conditions for single-glass, double-glass and a-Si semi-transparent PV modules integrated on the Trombe wall facades of a model test room.

In this article, the thermal performance comparison of single-glass, double-glass and building integrated photovoltaic Trombe wall systems has been made according to the experimental results taken from the test room built in Izmir, Turkey. The experimental measurement has been carried out to designate the thermal characteristics of the 3 systems. The temperature variations at certain nodes where the temperature probes are placed have been evaluated. The change in electrical efficiency by surface temperature of the a-Si PV module has also been interpreted.

2. Experimental study

A test room seen in Figure 1 has been built in the Heat Transfer Laboratory of Ege University Solar Energy Institute, Izmir. A-Si semi-transparent type PV, single glass and double glass have been attached to the south wall of the test room with an inter-space distance of 0.50m deep in between. Every module is 1.00 m wide and 2.56 m tall.

The test room has been insulated so well to minimize the heat loss to the surrounding and to increase the efficiency of 3 systems. The thermal wall consists of covering brick, vertical holed brick, extrude polystyrene and plaster from exterior to interior respectively. Extrude polystyrene and PVC plate has been used in ceiling insulation. The floor is of laminated flooring insulated with extruded polystyrene. The interior walls are of gypsum board insulated with glass wool. The solar radiation transmissivity of the a-Si semi-transparent PV module is 10%. The nominal power, open circuit voltage and short circuit current are 27W, 49V and 1.02A respectively (Kundakci Koyunbaba, B., Yilmaz, Z., 2012). Two vents of 0.40m × 0.20 m size are opened on the top and bottom of the thermal wall for each module. A small fan that fits the size of the vents is used to designate the effect of fan use in these systems.

In this article, the energy performance comparison of a-Si semi-transparent type PV, single glass and double glass integrated on the south façade of the test room has been made. The study aims to investigate the performance of Trombe wall under different exterior shell designs in heating period. The performance of BIPV Trombe wall combined with electricity generation and space heating has been evaluated via the experimental data. Experimental measurement has been carried out to designate the thermal characteristics of these systems. The experiments have been conducted during the days 19 - 21 January in heating period.

Figure 2 shows the locations of the temperature probes and the pyranometers in the test room.

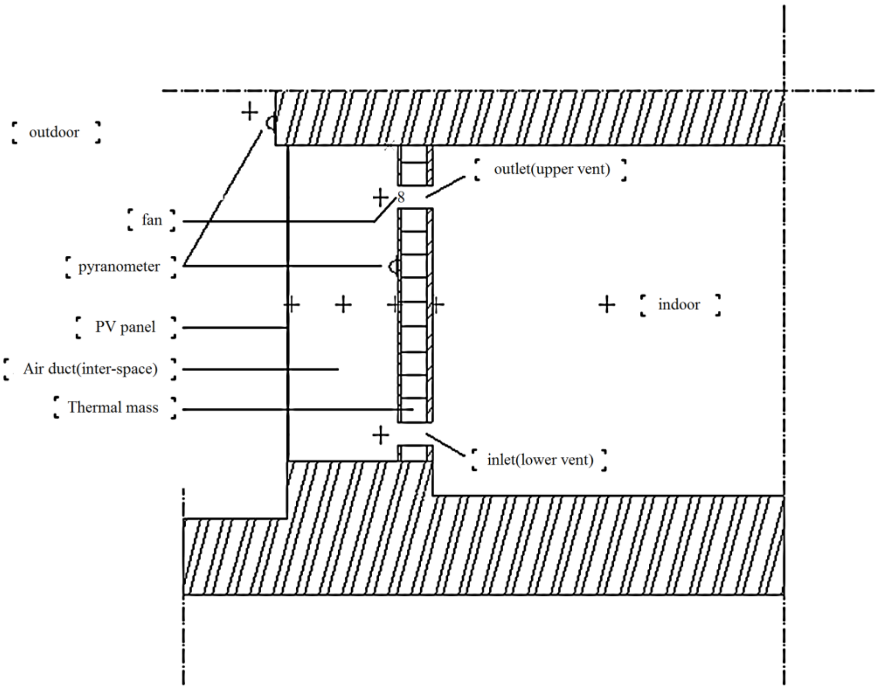

Figure 2. *Section of the test room when the vents are open for winter heating and the locations of the temperature probes and the pyranometers (Kundakci Koyunbaba, B., Yilmaz, Z., 2012).(+ Temperature testing point)*

The incident solar radiations on the exterior surface of the vertical south façade and the thermal wall of the PV module part have been measured by pyranometers every 10 minutes. The temperature values in certain locations of the room have also been measured by temperature probes seen in Figure 2 every 10 minutes and recorded by a datalogger. The air temperatures of ambient, in the inter-space, at the vents, on the exterior and interior surfaces of the thermal walls have been measured by probes.

3. Methodology

BIPV Trombe wall consists of a PV module, a thermal wall and an inter-space in between. There are two air vents opened on the thermal wall for winter heating. The electrical energy produced by a PV cell depends on its properties and the incoming solar radiation. The PV electrical efficiency is calculated by the traditional linear expression seen in the following equation (Evans, D.L., Florschuetz, L.W., 1977).

$$\eta = \eta_r \times \left[1 - \beta_r \times \left(T_{pv} - T_r\right)\right] \quad (1)$$

β_r is the temperature coefficient that is normally given by the PV manufacturer. The temperature coefficient of the a-Si semi-transparent PV used in this study is 0.002. T_{PV} is the average temperature of the PV cells, T_r is the reference temperature (25°C) and η_r is the reference efficiency of the PV cells. The reference efficiency of the PV cell is calculated with the equation below (Chow, T.T., 2010). The present value of reference efficiency is 4.5% at temperature of 25°C and solar intensity at 1000 W/m^2.

$$\eta_r = \frac{P_{mpp}}{I \times A} = \frac{V_{mpp} \times I_{mpp}}{I \times A} \tag{2}$$

V_{mpp} and I_{mpp} are the voltage and electric current at maximum power point operation. I is the incident solar irradiance normal to surface and A is the area of the photovoltaic cells.

η_r=4.5%

E is the electrical power rate generated by the PV glazing (W/m^2) and calculated using equation (3) (Ji et. Al, 2007a). I_{PV} is the solar radiation which arrives on the PV surface.

$$E = I_{PV} \times \eta_r \times \left[1 - 0.002 \times \left(T_{pv} - T_r\right)\right] \tag{3}$$

4. Results and discussion

Izmir has a Mediterranean Climate - Hot Summer according to Köppen-Geiger climate classification and is located in 38º23'N latitude, 27º04'E longitude and 29 m altitude. The yearly average ambient temperature is 17.93°C while the minimum and maximum values of the ambient temperatures for 33 years of observation results are -5°C and 43°C respectively. The yearly average temperature is high and has a high humidity level due to the region's being by the sea, its regional character, the height and the geographical location (Turkish State Meteorological Service).

Figure 3 shows the measured ambient conditions during 19 - 21 January. The hourly solar radiations on the vertical wall and the outdoor air temperatures are seen in the graph. As seen in the figure, the outdoor air temperatures take the maximum values of the day which are 22.4°C, 24.4°C and 24.88°C while the measured global solar radiations on the vertical surface of the PV module take the maximum values of the day which are 760.02/m^2, 716.63/m^2, and 784.78W/m^2 on 19 - 21 January.

In this study, single-glass, double-glass and PV module have been integrated on the exterior shell of the Trombe wall system in the test room to designate the performances. The experiments have been conducted in the winter period where heating is required. The temperature and global solar radiation values on the exterior shell and the thermal wall have been measured and recorded every 10 minutes. The hours the vents are opened and closed during experiments are seen in Table 1.

The three-day temperature change in the PV module part is seen in Figure 4. As seen in the figure, the temperature difference between the outdoor and the outlet air reaches up to 12.57°C at 18:00 on 19 January, 14.18°C at 17:00 on 20 January and 14.58°C at 18:00 on 21 January. Thus, the photovoltaic module part provides a remarkable temperature increase for the room. The vents are closed when the indoor air temperature reaches a higher value than the inter-space temperature. The vents are opened when the inter-space temperature reaches a higher value than the indoor air temperature. The heated air leaves the duct through the upper vent into the room and the cool air in the room enters the duct through the lower vent. Therefore, the room is heated and the surface of the PV module is cooled down which results in the increase in both indoor air temperature and electrical efficiency.

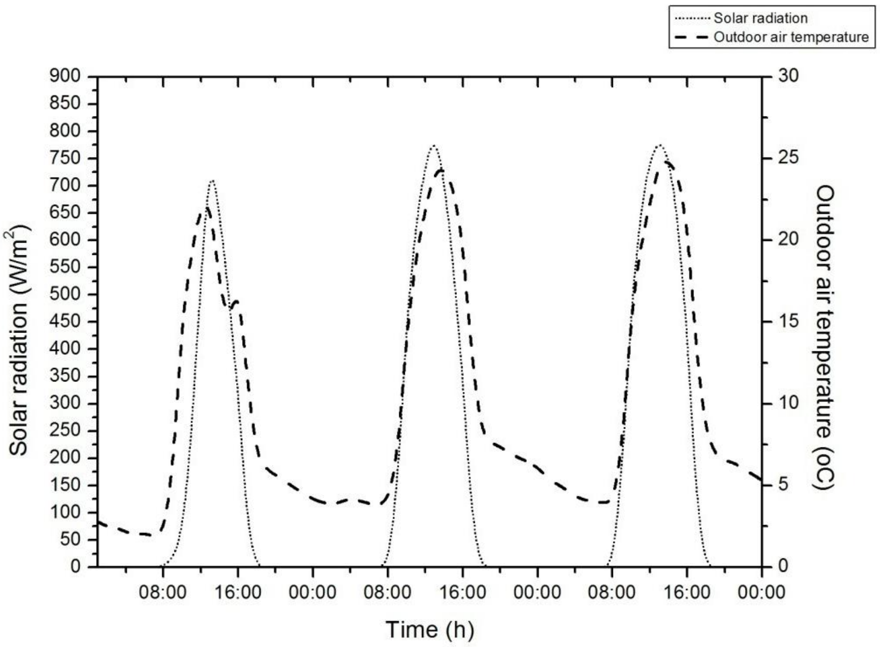

Figure 3. *The ambient conditions during 19 - 21 January.*

Table 1. *The hours the vents are opened and closed.*

Date	Opening hour	Closing hour
January 19th	12^{00}	17^{00}
January 20th	12^{00}	16^{00}
January 21th	12^{00}	16^{00}

Figure 5 shows the hourly temperature change in the double-glass part. The temperature difference between the outdoor and the outlet air reaches up to 14.17°C at 18:00 on 19 January, 16.42°C at 18:00 on 20 January and 16.93°C at 18:00 on 21 January. Thus, the increase in the room temperature provided by the double-glass part is higher than the PV module part.

Figure 6 shows the hourly temperature change in the single-glass part. The temperature difference between the outdoor and the outlet air reaches up to 12.63°C at 18:00 on 19 January, 14.83°C at 17:00 on 20 January and 14.73°C at 18:00 on 21 January.

Figure 7 shows the hourly outlet air temperature changes of the PV module, double-glass and single-glass parts. As seen in the figure, sudden fluctuations occur in indoor air temperature when the vents are opened and closed during the day. The hot air taken into the room through the upper vent and the cool air transferred from the room through the inter-space cause this sudden rise and fall in temperature values. The air flow through the vents occurs due to the buoyancy effect. During day time, the solar radiation that passes through the PV module, single and double-glass parts is absorbed by the thermal wall and is converted into energy. The energy is transferred by conduction and convection through the wall during the day and is released to the room by convection and radiation at night.

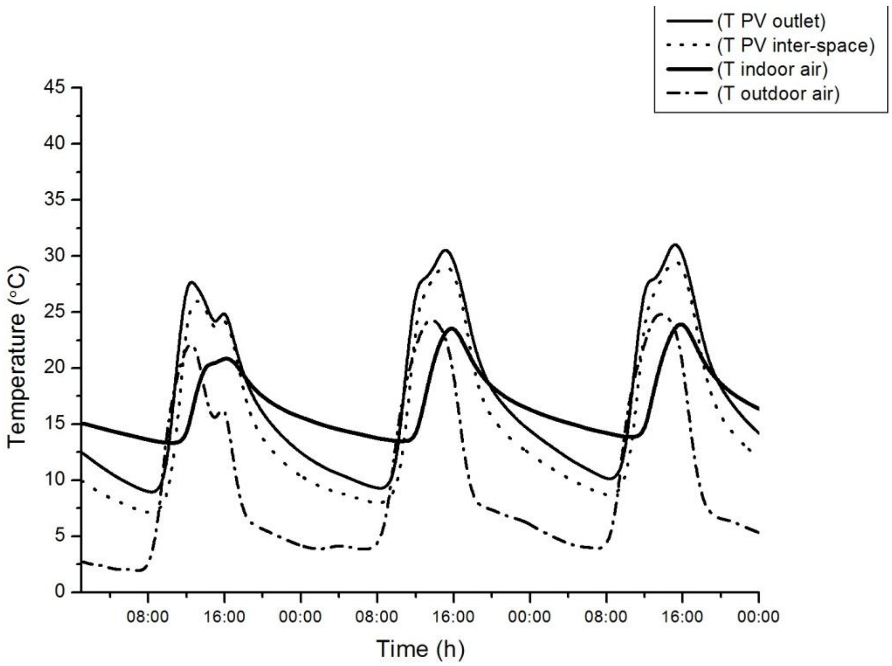

Figure 4. *The hourly temperature change in the PV module part.*

As double-glass reduces the heat loss to the surrounding due to its insulation character, it has higher temperature values than single-glass and PV module parts at night. As the transmissivity of single-glass is higher than double-glass and PV module, it has higher temperature values than the others during the day time when there is solar radiation [27].

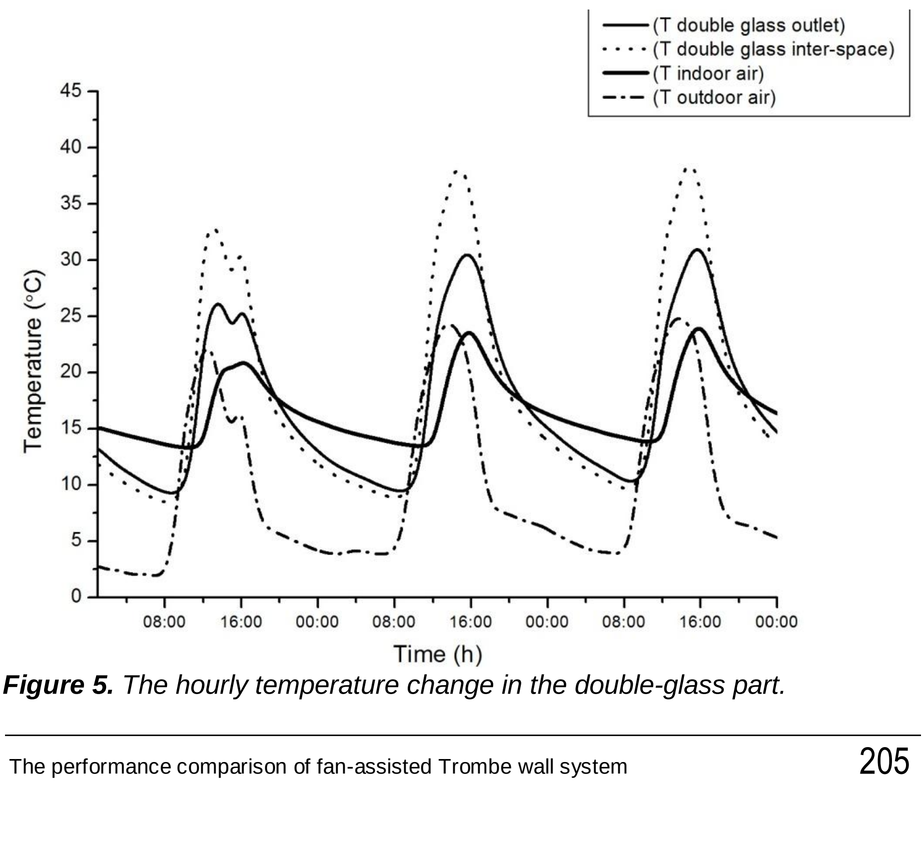

Figure 5. *The hourly temperature change in the double-glass part.*

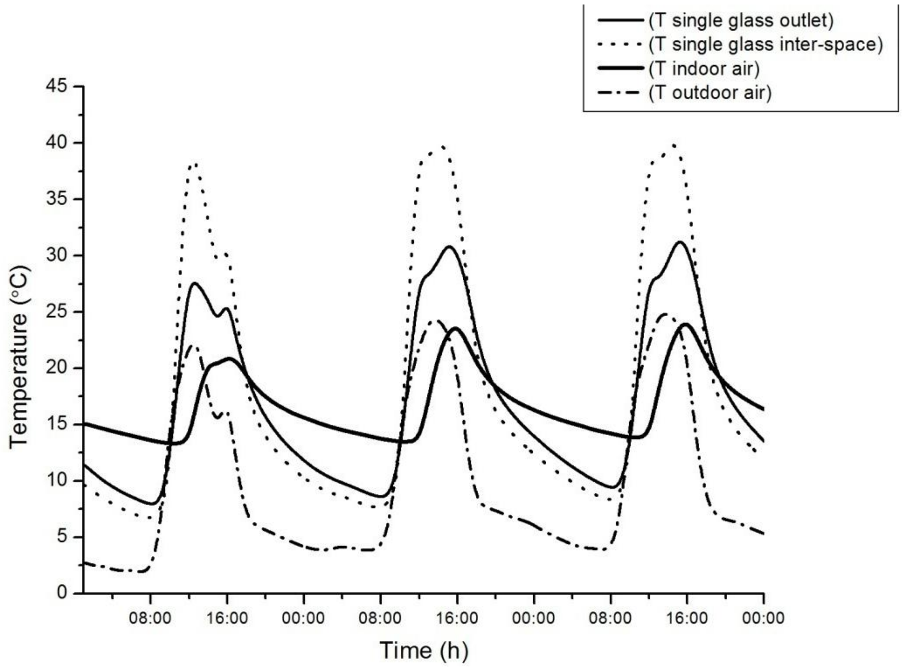

Figure 6. *The hourly temperature change in the single-glass part.*

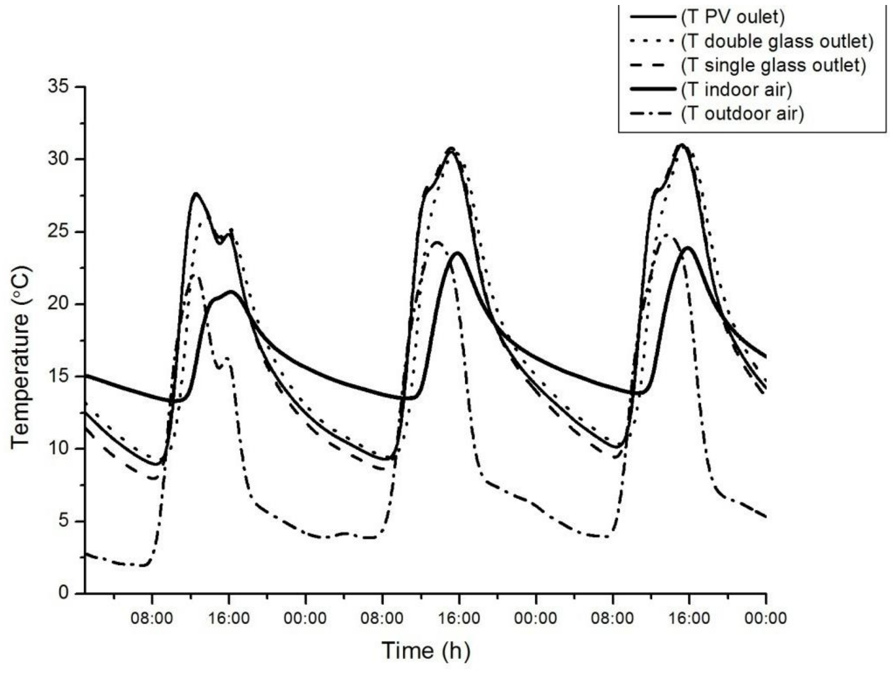

Figure 7. *The hourly outlet air temperature changes of the PV module, double-glass and single-glass parts.*

Figure 8 shows the hourly experimental data measured for the surface temperatures of the thermal wall and the PV module. During night time when the vents are closed and there is no solar radiation, the temperature values from higher to lower are wall inside surface, indoor air, wall outside surface, PV surface and outdoor air respectively. As the wall inside surface temperature is higher than the indoor air temperature, there is heat gain into the room by convection and radiation. There is also heat loss to the duct from the thermal wall and to the surrounding from the PV surface at night. When the vents are open and there is solar radiation during day time, the temperature values from higher to lower are PV surface, wall outside surface, outdoor air, indoor air and wall inside surface respectively. As the transmissivity of the semi-transparent PV module is 10%, the solar radiation that arrives on the thermal wall in the PV module part is much less than the double and single glass parts.

The hourly electrical efficiency change with PV cell surface temperature for 20 January is seen in Figure 10. PV electrical efficiency is calculated by equation (1) described in Methodology. The solar radiation is captured by PV cells to generate electricity. As seen in Figure 9, the electrical efficiency has its highest value of the day which is 0.0468 while the surface temperature of the PV cells has its lowest value of 5.58°C at 08:00. The electrical efficiency drops to its lowest value of the day at 14:00 which is 0.0435 when the surface temperature of the PV cells increases to its highest value of 41.32°C. Then, the electrical efficiency increases to 0.0453 as the surface temperature of the PV cells decreases to 21.65°C. Similar comments can be made for the other days. As a result, it can be concluded that as the surface temperature of the PV cells decrease, the electrical efficiency increases. This explains the necessity of cooling the PV module surface by opening vents on the thermal wall of BIPV Trombe wall. The energy performance comparison of these 3 systems without fan has been made in the previous paper of the authors (Kundakci Koyunbaba, B., Yilmaz, Z., 2012). It's obvious that the fan use causes temperature decrease in the systems which also causes the decrease in thermal efficiency of these systems. The electrical efficiency of the semi-transparent PV module increases approximately 0.1% which is a very small amount that can be ignored. As a result, the use of fan in these systems for winter heating is redundant.

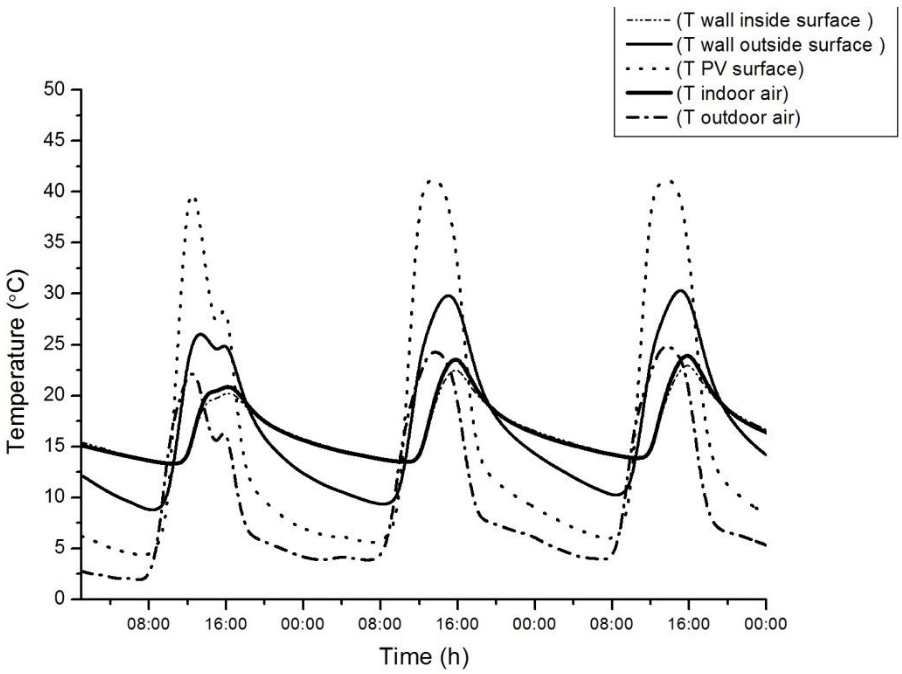

Figure 8. *The hourly temperature variations of the thermal wall and PV surface.*

Figure 10 shows the calculated hourly electrical power rate during 3 days' operation. The calculated values show that the electrical power rate is lower early in the morning and afternoon as the solar radiation intensity is low during those hours whereas it reaches up to 34.61 W during 19 - 21 January.

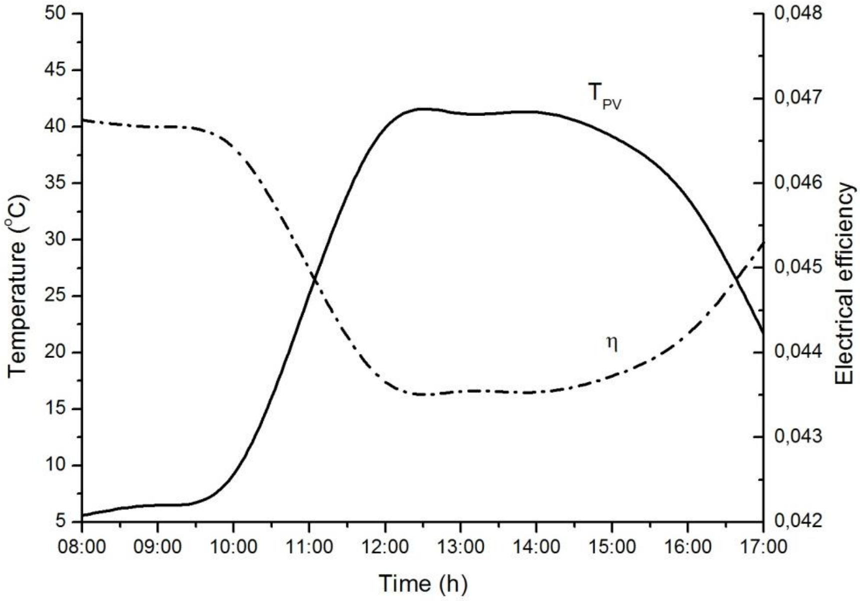

Figure 9. *The hourly electrical efficiency change with PV cell surface temperature 20 January.*

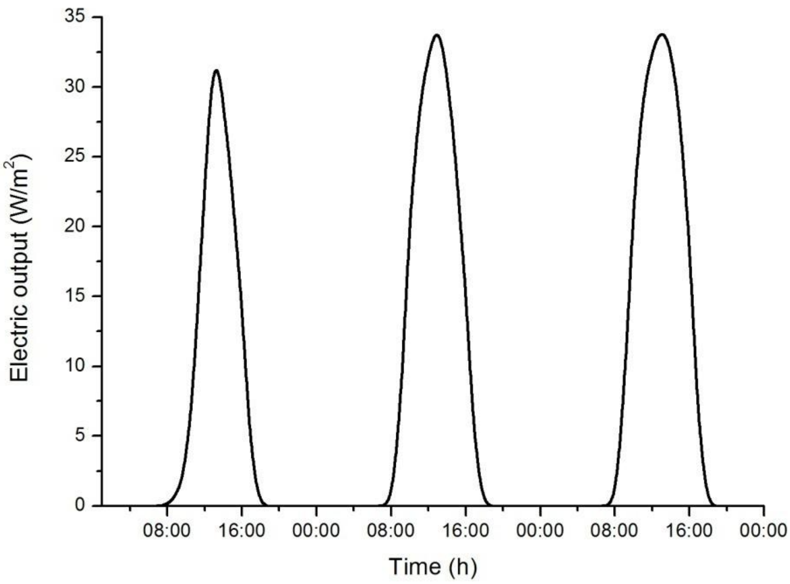

Figure 10. *The hourly variation of the electrical power rate for 19 - 21 January.*

5. Conclusion

The experiments have been performed in a test room constructed in Ege University campus in Turkey. The temperature and solar radiation values on the exterior surface of the south wall and the thermal wall of the PV module part have been measured every 10 minutes during 19 - 21 January.

The aim of this paper is to investigate the performances of fan-assisted single-glass, double-glass and BIPV Trombe wall systems by drawing a comparison between the experimental results. A test room has been built to take measurements from these 3 systems. The semi-transparent a-Si PV module has a solar radiation transmissivity of 10% which allows smaller amount of solar radiation to arrive onto the thermal wall.

The insulation character of double-glass is much better than single-glass and PV module. Therefore, it reduces the heat loss to the surrounding at night. This is important for winter heating. Besides, the application of single-glass with a shutter for night time and evening insulation provides higher thermal performance than the double-glass application. The a-Si PV cells have an average electrical efficiency of 4.5% according to 3 days of experimental results. Therefore, BIPV Trombe wall is an efficient way of producing both heat and electricity for the climatic conditions of Izmir (Kundakci Koyunbaba, B., Yilmaz, Z., 2012).

The integration of PV cells reduces the thermal efficiency of Trombe wall in terms of heat gain, whereas the electricity generation is accepted as a benefit. The efficiency of the PV cells increases as the heat on their surface is absorbed by the air circulated between the inter-space and the room when the vents are open. The integration of PV module instead of glass makes the look of the Trombe wall façade more appealing in aesthetic means. Trombe wall system is an energy efficient solar system that is easy to apply on the south facing facades of existing buildings as well as new ones.

The fan use in 3 of the systems causes the decrease in both temperature and thermal efficiency. Besides, the increase in electrical efficiency of the semi-transparent PV module is redundant.

In this paper, the experimental results of 3 systems have been evaluated and commented on. The performance of these systems with fan for summer period may be considered as a future study.

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Fan entegre edilmiş Trombe duvarlı sistemin performans kıyaslaması

Binalarda enerji korunumu için kullanılan çeşitli sistemlerden biri de binaya entegre fotovoltaik (BEFV) Trombe duvarlı sistemdir. Bu sistem, binaların güneye bakan kör cephelerine ısı ve elektrik üretmek için uygulanmaktadır. Bu çalışmada, İzmir'de model bir test odasında fan entegre edilmiş tek cam, çift cam ve a-Si yarı-geçirgen FV modüllü Trombe duvarlı sistemin enerji performans kıyaslaması yapılmaktadır. Sistem, 19-21 Ocak tarihlerinde çalıştırılmıştır. Sıcaklık sensörlerinin yerleştirildiği noktalarda ölçülen sıcaklık değişimleri değerlendirilmiştir. Tek cam, çift cam ve FV modülde ölçülen üst ve alt menfez sıcaklıkları karşılaştırılmıştır. Ayrıca, FV modül ve termal kütlenin yüzey sıcaklıkları değerlendirilmiştir. 3 modülün termal performansları deney sonuçlarına göre kıyaslanmıştır. FV modülün yüzey sıcaklığına bağlı elektriksel verimindeki değişim yorumlanmıştır. Deney sonuçlarına göre, yarı-geçirgen FV modülün güneş ışınımı geçirgenliği %10'dur. Sonuç olarak, deney sonuçlarına göre FV hücrelerin elektriksel verimi %4.5'a ulaşmaktadır.