Ventilation benefit accrued from PV module installed in building

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ABSTRACT

Solar radiation is an important source of heat gain into the building and plays an important role as far as thermal comfort in a dwelling is concerned. In summer and in hot climate regions, the thermal gain of a building exceeds the thermal comfort level of the inhabitants and cooling is desirable. The high insolation may be utilized to provide the necessary ventilation cheaply. In this study, we propose to use photovoltaic (PV) system installed in a building to provide natural ventilation by adopting it as a Roof Solar Collector (RSC) and modifying the air channel by inserting a Thin Flat Metallic Sheet (TFMS) in the middle of the channel to enhance the natural flow and also reduce the roof temperature by acting as a “shield”. The results show that the modified system does increase the thermal efficiency of air resulting in higher temperature rise hence airflow rate.

1. INTRODUCTION

In the countries located in the tropics and along the Mediterranean region, heat gain in summer in residential buildings is a problem and cause thermal discomfort to the residents. Mechanical air-conditionings (A/C) are usually employed to satisfy their thermal comfort. Considering today’s economic crisis, energy conservation programs and the concern on the environment, there is a need to re-examine the general design practices and application of A/C in building sector with a view of reducing over reliance on them or convectional energy sources for that matter. In the residential and tertiary buildings, use of innovative technology, including the renewable energy, is one method of reducing energy consumption in these sectors.

Natural cooling and ventilation of a building is a simple, cheap and energy saving method of achieving acceptable thermal comfort and indoor air quality for the occupants especially in developing countries. Natural ventilation is caused by the pressure difference between the inlets and outlets of the building envelope. Night ventilation, wind towers, Trombe walls and solar chimneys are the main natural ventilation techniques. Ground, evaporative and radiative cooling can also be used for building cooling. Solar air collectors can be integrated in the building roof to form the Roof Solar Collector (RSC) and operates on stack effect to induce natural air circulation from inside to the outside of the building (Awbi, 1998). The RSC has attracted a lot of attention in the recent past especially in the natural ventilation applications in buildings and many works are reported.

Khedari et al., (1997) has done extensive studies on RSC using the roofing tiles to make absorber plate for natural ventilation of building in Thailand and gave minimum dimensions regarding the air gap size, opening vents and the length of the RSC to induce adequate air flow rate. Hurunlabb et al., (2001) studied RSC of different configuration and using metallic plate for absorber plate and gave results regarding their orientation and incorporation into the building roof. Regarding the performance during hot season, the above authors observed that the simple RSC will not meet the required ventilation level and recommended the use of PV driven fan to enhance air flow rate (Khedari et al., 2002). Gan (1998) used the computational fluid dynamics technique (CFD) to simulate a

Trombe wall for summer ventilation and investigated the influence of various parameters on the performance of Trombe wall. Chen et al. (2003) did experimental and theoretical studies on a simple solar chimney with uniform heat flux on one wall and gave results for air temperature and airflow rates for different chimney gaps, heat fluxes and different chimney inclination angles. Raman et al. (2001) describes various aspects of a passive solar air collector that can be used to provide thermal comfort conditions inside the building year-round. Moshfegh and Sandberg (1998) investigated the flow and heat transfer characteristics of buoyancy-driven air flow behind PV panel. On the determination of the induced ventilation rate, Dascalaki (1996) used tracer gas technique to measure air velocity hence derive airflow rate, in their single-ended ventilation configuration model.

Other works on theoretical and experimental studies of natural ventilation of buildings includes those by Gan and Riffat (1998), Erell and Etzion (2000), Li (2000), Rodrigues et al (2000), Dai et al (2003), and Zhai et al (2004). The general trends of all these investigations are oriented towards seeking of new configurations to enhance the heat transfer parameters or the optimization of standard configurations. Extensive methods and tools developed for natural ventilation processes are included in the Design Handbook of Santamouris (1998). Detail treatments of other alternative methods of buildings cooling are referred by Santamouris (1995) and Jacovides (1995) regarding earth-to-air heat exchangers.

Hybrid Photovoltaic/Thermal (PV/T) systems are new type of solar energy devices that provide electricity and heat simultaneously. They consist of PV panels and thermal units mounted together as integral unit. The thermal unit, employing low temperature circulating fluid, is used to extract the absorbed sunlight that is not converted into electricity by the PV cells. Several studies have been done and reported on PV/T solar collectors. Extensive studies on water and air cooled PV/T collectors have been presented by Tripanagnostopoulos et.al (2000, 2001 and 2002a) who gave extensive experimental results of their studies and detailed references. Tripanagnostopoulos et.al (2002b) also did experimental and theoretical study of a modified PV/T air system employing a low cost Thin Flat Metallic Sheet (TFMS) for heat extraction improvement from the PV panel.

In this work we propose to adopt a PV module or array installed in a building to provide passive cooling by operating it as a solar roof collector with PV panel as absorber plate. An air channel arrangement is attached at the back of the module for air circulation. Low cost improvement of air flow rate is suggested where a Thin Flat Metallic Sheet (TFMS) is inserted in the middle of the air channel as a baffle sheet. The TFMS enhances the heat extraction from the panel resulting in high exit air temperature hence ventilation rate and also to provide "shading" to the roof reducing heat conduction to the interior of the building.

2. BASIC CONCEPT OF PV/T COLLECTOR

A PV module generates electric current (DC) directly from sunshine. They absorb about 80% of the incident radiation and out of this convert about 5-15% only (depending on technology) into electricity and the rest is converted into waste heat. However, this excess heat may be recovered for practical application by attaching a heat exchanger behind the module yielding hybrid Photovoltaic/Thermal (PV/T) collector. The PV/T solar collector is able to produce thermal and electric energy simultaneously and is considered interesting alternatives for solar application, especially in cases where limited space (e.g. southern-facing roofs in Europe) and area related cost is the primary concern. The PV/T systems are categorized according to the mode of heat extraction thus *PV/T-water* and *PV/T-air* systems. The PV/T-water system utilized water as heat transport medium while PV/T-air utilized air. The PV/T water is more efficient than PV/T air but cost more and can be used for domestic hot water supply. The PV/T air, on the other hand, is a simple and cheap means of extracting heat from the PV panel and can be used to produce warm air for space heating or cooling and drying needs in both agricultural and industrial sector. The schematic diagram of our PV/T air models are illustrated in Figure 1, for normal and modified (to be referred here after as REF and TFMS respectively).

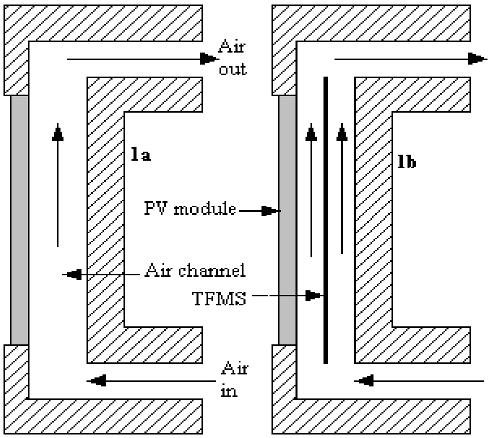

Figure 1: Cross section of the PV/T air system, REF (1a) and TFMS (1b).

The REF system has a simple air duct attached at the back of the module and the TFMS has a similar duct but modified by inserting a thin sheet of metal (aluminum) and behave like a parallel double pass air channel increasing heat extraction surface. The air circulation behind the PV panel lowers module temperature improving the solar efficiency since it decreases with increasing module temperature. In addition, the controlled warm air in the channel can be used for winter preheating or summer cooling.

3. EXPERIMENTAL STUDY OF THE PV/T AIR SYSTEM

In our laboratory, we investigate various innovative designs on the improvement of heat extraction from the PV/T air collectors. Our prototype PV/T air models consists of two identical systems made from pc-Si PV panels (46 Wp) and one is used as a reference (REF) and the other one as modified (TFMS) system. A rectangular air channel, of depth 15cm, is constructed at the rear of each module by using a thermal insulator board to make the back and sides of the channel and lined with a thin aluminum sheet on the inside surfaces. Inlet and outlet vents of equal sizes are provided at the bottom and top of the air channel respectively. The TFMS has the side facing the panel painted black to increase its absorptivity and the other side left unpainted.

The systems are mounted on a mobile track and tilted at an angle of 40^o. Copper-Constantan (Cu-CuNi) thermocouples are used to measure the temperatures of systems components and air inlet and outlet temperature in the channel and the ambient temperature. A Kipp & Zonen pyranometer and a three cup anemometer are used to measure the solar insolation, I_r, at the plane of the module and the wind velocity, V_w above the systems respectively. The experiment is performed outdoor and the system oriented due south and run by free convection and data is recorded by CR10X data logger. Appropriate resistive load is connected across each module output and assumed to bias them at their maximum power point (MPP) all the time.

The PV/T air system is to be mounted in the building roofs as a roof solar collector (RSC). The PV/T collector acts as an exhaust fan by sucking the room air and venting it out during sunshine hours. In the reference system, the PV panel absorbed incident solar radiation and transfers heat to air in the gap by convection and back wall by radiation. The back wall temperature rises and in turn, together with the PV module, heats up the air in the gap. The same process also occur in the modified system but now the heat transfer surface is doubled by inclusion of TFMS which acts as intermediate heat transfer surface between the PV panel back surface and the back wall. Consequently, air rises and leave the channel at the top vent and is replaced by air from the house which in turn is substituted by fresh air induced into the house providing the desired comfort sensations. The system is to be appropriately coupled to the building to avoid back drafting of air flow into the building.

4. PERFORMANCE OF A MODIFIED PV/T AIR SYSTEM

Figure 2 gives thermal performance curves for the REF and TFMS systems with (GL) and without (UNGL) additional glazing as a function of $\Delta T/G$ ($\Delta T = T_i - T_a$, T_i and T_a are air inlet and ambient temperature respectively and G is incident irradiance). As shown by the curves, the thermal efficiency of the modified system is higher than the reference system indicating that the heat transfer to air in the modified system is increased, hence high heat

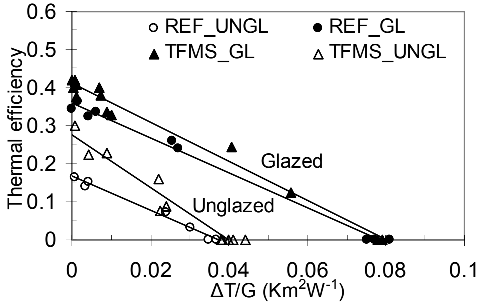

Figure 2: Thermal efficiency for REF and TFMS systems.

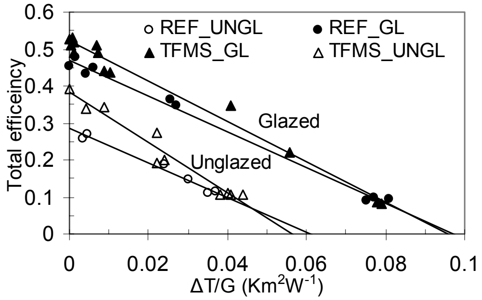

Figure 3: Total efficiency for REF and TFMS systems.

gain by airflow. This achieves high temperature rise resulting in high buoyancy force hence high airflow rate and ventilation rate required for effective cooling. The glazing also improves thermal efficiency for both systems as indicated by the curves in the graph of Figure 2.

The total performance (electrical + thermal) for each system is given in Figure 3 in terms of the reduced temperature ratio, ΔT/G. We observe that the total performance of TFMS system is higher than the REF system in both glazed and unglazed systems as expected.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Our interest in these experiment were to investigate the possibility of using the heat recovered from the PV panel installed in a building (and intended to meet its electrical loads) to provide ventilation in summer also with minimal additional cost. The parameters that were monitored are the system components' temperatures as well as the output temperature of air together with the ambiance conditions. The pressure drops and induced air flow velocities are calculated and compared with the results from others.

Figure 4 shows sample results of the hourly variation of the back wall and output temperature for both systems together with the prevailing ambiance. T_1 and T_2 are the back wall temperatures while T_3 and T_4 are the output temperatures for the TFMS and REF systems respectively.

The temperatures are changing with irradiance as expected. From 12:00 pm to 3:00 pm, high values are generally observed for the walls and outputs temperature due to high irradiance. As the radiation starts decreasing in the afternoon, the air outputs temperatures starts to decrease but the back wall temperatures tend to remain constant (stagnate) until the radiation is about 700 W/m^2 when they also fall. The output airflow temperatures depend strongly on the instantaneous irradiance and thus its flow rate is self regulating with irradiance level. In other words, the flow rate is high during high insolation period, resulting in the required high ventilation rate and vice versa. The back wall temperature for the TFMS system is lower than that of the REF system since the TFMS "shades" the back wall. This is an added advantage because, apart from improving flow rate, it will also lower back wall (roof) temperature and reduces the heat transfer to the building by conduction through the roof material hence reducing the cooling load of the building in addition.

The buoyancy force causes air flow in solar chimney and this force is proportional to the difference between the mean air density within the chimney and the ambient air density. The

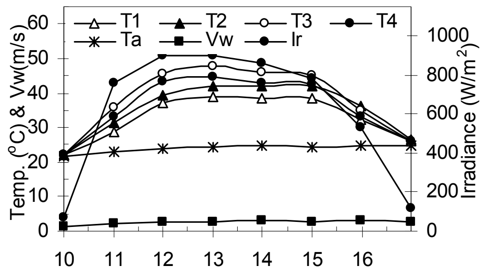

Figure 4: Hourly variation of system temperatures and ambiance conditions.

pressure drop, ΔP due to the buoyant pressure head can be calculated from the equation given by Ekechukwu and Norton (1997) and considering the inclination of the PV/T system:

$$\Delta P = g(L\sin\theta)(\rho_a - \rho_{ch}) \quad (1)$$

where g is the gravitational constant (m/s), L is the length of air channel (m), θ is the inclination angle (^{o}), ρ_a and ρ_{ch} are average densities of the ambient air and the air in the channel (Kgm^{-3}).

Expressing equ. (1) in terms of air channel and ambient temperatures, T_{ch} and T_a respectively gives:

$$\Delta P = \beta g \rho_o L \sin\theta (T_{ch} - T_a) \quad (2)$$

where β is the coefficient of volume expansion of the air and is equal to the reciprocal of absolute temperature for an ideal gas (1/K).

The pressure drop is caused by the resistance (friction) of the walls of the duct and using Darcy-Weisbach equation and equ. (2), the air velocity is given by:

$$\upsilon = \left[\frac{2D_H \beta g \sin\theta}{f}\left(T_{ch} - T_a\right)\right]^{\frac{1}{2}} \quad (3)$$

For the data of Figure 4, the average hourly values of the pressure drops and air flow velocities for each system were calculated from equs. (2) and (3) based on the inlet-outlet temperature of air and presented in graphical form in Figure 5. The TFMS system results in higher pressure drop, hence air velocity, than REF systems due to more contact surface area between airflow and duct walls hence more frictional losses.

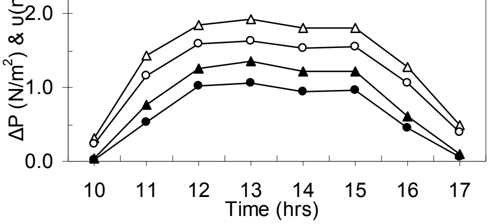

Figure 5: Hourly pressure drops and airflow velocities of both systems.

The friction factor, f in equation (3) was calculated from the formula given below (White, 1994):

$$f = \left(2.0\log\frac{3.7D_H}{\varepsilon}\right)^{-2} \quad (4)$$

where ε is the average wall roughness height and is assumed to be 2.4 mm (corresponding to smooth painted steel, White (1994)). The velocities values obtained are in close agreement with those obtained by others (see Khedari et al., 1997). It should be noted that the wind speed was about 2.5 m/s during the test and may have enhanced the air circulation in the channels hence increasing average air velocity.

6. CONCLUSIONS

The possibility of using PV/T system for natural ventilation of building has been demonstrated. The sample results indicates that the PV temperature can be of the order of 25^{o}C or beyond above the ambient temperature. The output temperature of air in the channel is higher than the ambient and would produce the desired buoyancy-induced airflow through the channel. Noting that a single PV module is used in this study whereas in practical PV installation or in BIPV, large array areas are involved, then the thermal energy intercepted will produce high exit temperature inducing enough airflow rates required for good natural ventilation.

From the simple analysis, it is evident that the airflow rate is in good agreement with the existing results for practical RSC used in building ventilation. The low cost improvement of the heat extraction by interposing TFMS in the middle of the channel increases the thermal efficiency and provides "shading" by about 3^{o}C. The ventilation rate may be improved by taping part of the electricity generated by the PV module to drive a low power fan to enhance airflow during hot seasons.

ACKNOWLEDGEMENT

The first author would like to acknowledge IKY-Greece for the scholarship award.

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