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M Imroz Sohel
University of Wollongong, msohel@uow.edu.au

Zhenjun Ma
University of Wollongong, zhenjun@uow.edu.au

Paul Cooper
University of Wollongong, pcooper@uow.edu.au

Jamie Adams
BlueScope Steel Limited

Robert Scott
Blue Scope Steel Limited

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Abstract

In this paper we present a theoretical investigation of an air based solar photovoltaic thermal (PVT) system integrated with phase change materials. The advantage of the air based PVT system is that the air can be directly used for space heating or cooling. At first we present an air based PVT system model and analyze the effect of major parameters on the system performance. We then integrate this PVT system model with a phase change material (PCM) energy storage system model and analyze the system performance. We found that solar irradiation increased thermal efficiency initially before reaching a plateau. However, electrical efficiency increases almost linearly with the solar irradiation. Increasing the air flow rate through the air channels, both the thermal and electrical efficiencies increase. Our results also showed that the channel depth has limited effect on the PVT system, only up to certain depth. The wind speed showed significant effect. As wind speed increases, the thermal efficiency decreases. This is due to the fact that with higher wind speed, much of the heat from the PVT surface (which is unglazed) is lost to the environment. This cools the PV plate and consequently increases its electrical efficiency. Our initial results also suggest that air based PVT system can supply considerable part of required space heating energy for a typical household. Incorporating PCM into PVT system enables the system to supplement heating, ventilation and air-conditioning energy demand even when the sun light or night cooling is not available.

Keywords

change, phase, integrated, system, materials, thermal, theoretical, photovoltaic, solar, investigation

Disciplines

Engineering | Science and Technology Studies

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A Theoretical Investigation of a Solar Photovoltaic Thermal System Integrated with Phase Change Materials

M. Imroz Sohel[1*], Zhenjun Ma[1], Paul Cooper[1], Jamie Adams[2] and Robert Scott[2]

[1]Sustainable Building Research Centre, University of Wollongong, NSW 2522, Australia
[2]BlueScope Research, Port Kembla NSW 2505, Australia

[*]Corresponding author: msohel@uow.edu.au

ABSTRACT

In this paper we present a theoretical investigation of an air based solar photovoltaic thermal (PVT) system integrated with phase change materials. The advantage of the air based PVT system is that the air can be directly used for space heating or cooling. At first we present an air based PVT system model and analyze the effect of major parameters on the system performance. We then integrate this PVT system model with a phase change material (PCM) energy storage system model and analyze the system performance.

We found that solar irradiation increased thermal efficiency initially before reaching a plateau. However, electrical efficiency increases almost linearly with the solar irradiation. Increasing the air flow rate through the air channels, both the thermal and electrical efficiencies increase.

Our results also showed that the channel depth has limited effect on the PVT system, only up to certain depth. The wind speed showed significant effect. As wind speed increases, the thermal efficiency decreases. This is due to the fact that with higher wind speed, much of the heat from the PVT surface (which is unglazed) is lost to the environment. This cools the PV plate and consequently increases its electrical efficiency.

Our initial results also suggest that air based PVT system can supply considerable part of required space heating energy for a typical household. Incorporating PCM into PVT system enables the system to supplement heating, ventilation and air-conditioning energy demand even when the sun light or night cooling is not available.

KEYWORDS: *Solar photovoltaic thermal; modelling; thermodynamics; solar energy, phase change material (PCM).*

1 INTRODUCTION

Performance of a solar photovoltaic (PV) system deteriorates with increasing temperature [1]. In a solar photovoltaic thermal (PVT) system excess heat from a PV is removed and used for space heating, domestic hot water or other useful means. The benefit of a PVT system is twofold: collecting more energy and lowering PV temperature [2]. Moreover, the PVT system suggested to have higher cost-effectiveness [3]. PVT systems can be either liquid based or air based [4]. While most of the PVT systems in the literature are water based, a good number of articles on air based system are also available in the literature [2, 5-8]. The water based systems have superior performance compared to the air based systems due to enhanced heat transfer characteristics [9]. However, the air based systems have the advantage that air can be directly used for space heating.

In current literature a significant effort in research and development in phase change materials (PCM) is noticeable [10-12]. PCMs are useful in storing the solar thermal energy during the day and use at night. Same way, PCMs can also be used to store night radiant cool [13] and use during the day.

In this paper, first we present an air based PVT system model and analyze the effect of major parameters on the system performance. We then integrate this PVT system model with a phase change material (PCM) energy storage system model and analyze the system performance.

2 MATERIALS/METHODS

Fig. 1 presents a schematic of the air based PVT system design. PV panels based on the thin-film technology are fitted onto profiled metal roofing. Air passes through the channels underneath the PV panel taking the excess heat from the PV panels. The model was developed in Matlab [14] based on the TRNSYS [15] PVT model "Type 560" with appropriate modification.

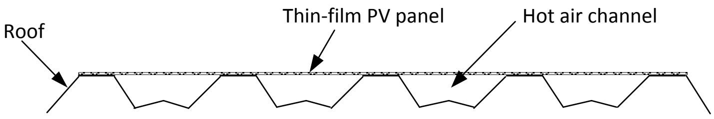

Fig. 1 Schematic of the PVT system used for modelling purposes

For simulating the building heating load, we have used TRNSYS simple building model and weather data of Sydney. A single storied 200 m^2 floor area building with total surface area of 580 m^2 was considered in this simulation. We considered a separate

PCM heat storage system for this analysis. A simple PCM model based on average effectiveness [16] was used to calculate energy storage capacity and discharge time. For modeling PCM storage system, we have assumed commercial salthydrate PCM brick type storage [17] with melting temperature 22 ˚C, density 1520 kg/m^3, latent heat 160 kJ/kg, specific heat 1.9 kJ/kg.K, thermal conductivity 0.43 W/m.K and capacity 46 kWh/m^3.

3 RESULTS AND DISCUSSION

3.1 Effect of PVT parameters

The effect of solar irradiation on the PVT performance

In this section the effect of solar irradiation on the PVT system is presented. For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; air flow rate, $\dot{V}$ = 20 l/s per channel; ambient temperature, T_{amb} = 20 ˚C; wind velocity, $\dot{v}$ = 5 m/s; channel depth, d= 0.03 m; PVT length, l= 1 m; and reflectance of the PV surface, ρ = 0.15 (dimension less).

Fig. 2 presents the effect of solar irradiation on the air outlet temperature from the PVT system and the PV plate mean temperature. Increasing the solar irradiation from 100 W/m^2 to 1000 W/m^2, the air outlet temperature has increased from 21 ˚C to 33 ˚C while the PV plate mean temperature has increased from 22 ˚C to 85 ˚C.

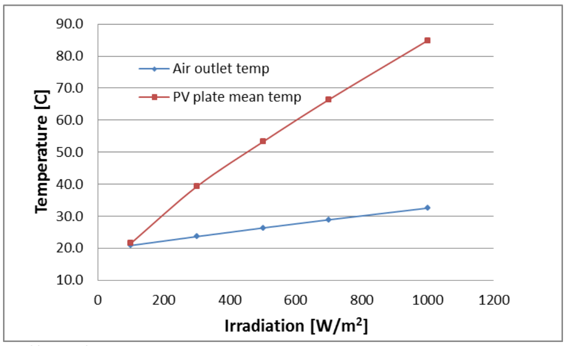

Fig. 2: Effect of solar irradiation on air outlet and PV mean plate temperatures

Fig. 3 presents the effect of solar irradiation on the thermal efficiency and the collector heat removal factor. Heat removal factor is defined as the ratio of actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature [18]. By increasing solar irradiation both thermal efficiency and collector heat removal factor increases initially. However, they both plateau at about 400 W/m^2. Fig. 4 presents the effect of solar irradiation on the electrical efficiency. The electrical efficiency increases almost linearly with the solar irradiation.

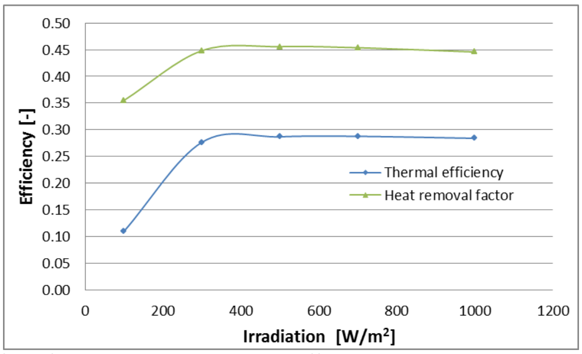

Fig. 3: Effect of solar irradiation on thermal efficiency and collector heat removal factor

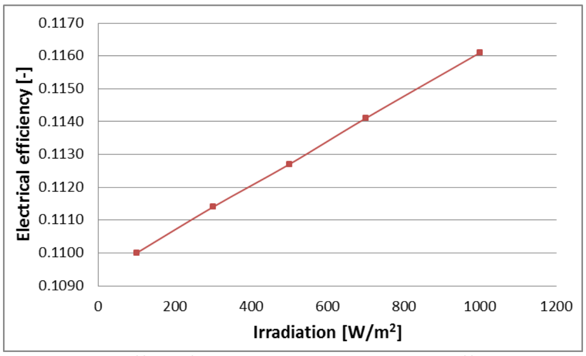

Fig. 4**:** Effect of solar irradiation on electrical efficiency

The effect of air flow rate through the channels

The effect of air flow rate through the channels on the PVT system is presented here. For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; solar irradiation, I= 700 W/m^2; ambient temperature, T_{amb} = 20 ˚C; wind velocity, $\dot{v}$ = 5 m/s; channel depth, d= 0.03 m; PVT length, l= 1 m; and reflectance of the PV surface, ρ = 0.15 (dimension less). Increasing air flow rate through the channels, both the air outlet temperature and the PV plate mean temperature decrease (Fig. 5).

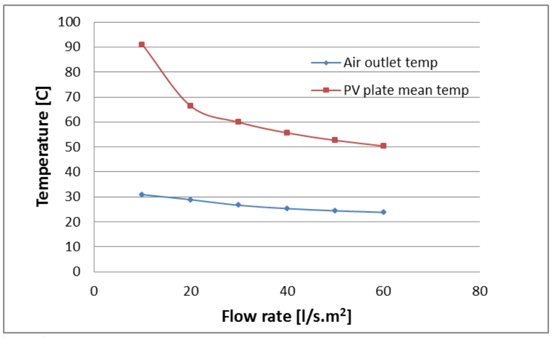

Fig. 5: Effect of air flow rate through the channels on air outlet and PV mean plate temperatures

Consequently, the thermal (Fig. 6) and electrical (Fig. 7) efficiencies increase 100% and 2%, respectively. However, increased air flow requires higher pump work. Therefore, a trade-off required between the increased efficiency and the pump work. A further investigation to analyze the effect of air flow rate through the channels is warranted.

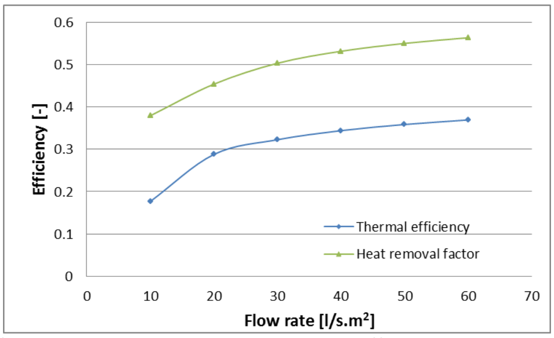

Fig. 6: Effect of air flow rate through the channels on thermal efficiency and collector heat removal factor

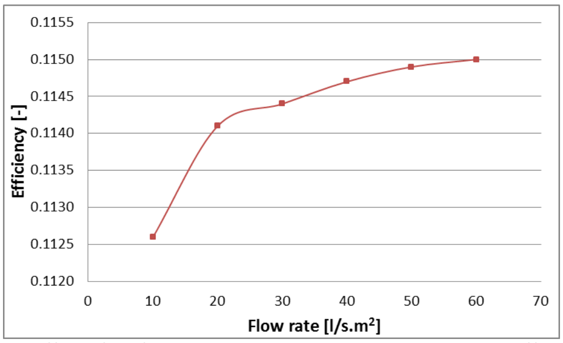

Fig. 7: Effect of air flow rate through the channels on electrical efficiency

The effect of channel depth on performance

For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; solar irradiation, I= 700 W/m^2; ambient temperature, T_{amb} = 20 ˚C, air flow rate, $\dot{V}$ = 20 l/s per channel; wind velocity, $\dot{v}$ = 5 m/s, PVT length, l= 1 m; and reflectance of the PV surface, ρ = 0.15 (dimension less). Our simulation results show that channel depth has limited effect on the PVT system, only up to about 0.1m (Fig. 8, 9 and 10). This results is in line with the literature where the optimum channel depth is suggested to be about 0.1 m [19]. In that study, Gan (2009) has used CFD analysis to find out the optimum channel depth.

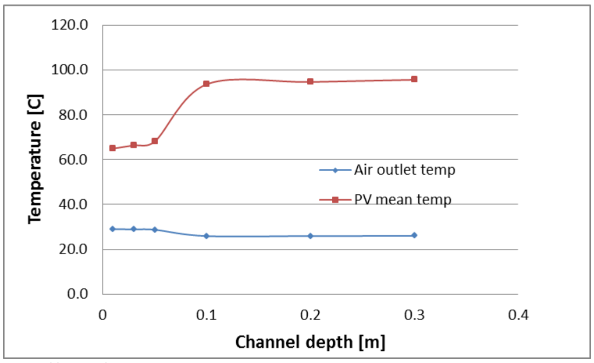

Fig. 8: Effect of channel depth on air outlet and PV mean plate temperatures

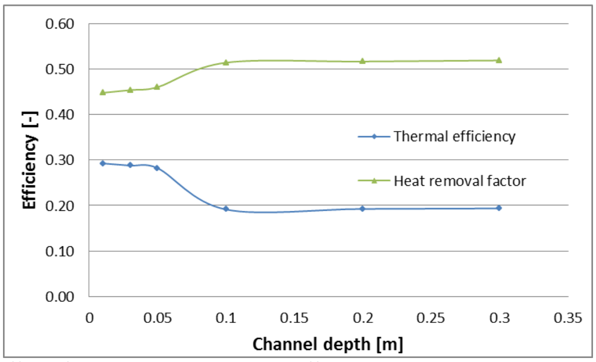

Fig. 9: Effect of channel depth on thermal efficiency and collector heat removal factor

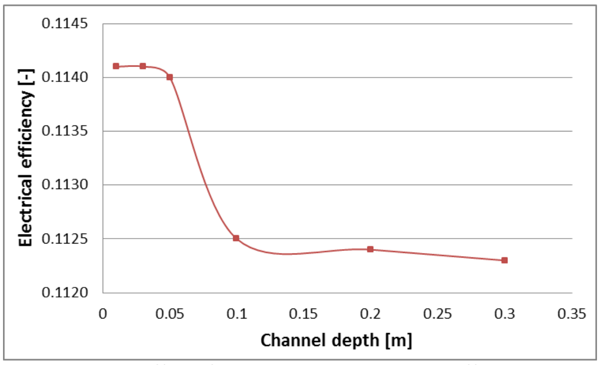

Fig. 10: Effect of channel depth on electrical efficiency

The effect of PVT length on performance

The effect of PVT length on the PVT system is presented here. For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; solar irradiation, I= 700 W/m^2; ambient temperature, T_{amb} = 20 ˚C; $\dot{V}$ = 20 l/s per channel; wind velocity, $\dot{v}$ = 5 m/s; channel depth, d= 0.03 m; and reflectance of the PV surface, ρ = 0.15 (dimension less).

If we increase the PVT length the thermal efficiency decreases (Fig. 11) but electrical efficiency increases up to l= 5 m, then it remains nearly unchanged (Fig. 12). With constant flow rate as the length increases, the PVT material becomes hotter on an average and consequently thermal efficiency decreases. Due to high temperature difference at the entrance, more heat is transferred from PV plate to the air and the electrical efficiency increases initially but after l= 5 m, the heat transfer rate is small and the electrical efficiency remains almost unchanged. An optimum length requires a trade-off between electrical and thermal efficiencies. However, as electricity is a pure form of energy (exergy) and heated air is low grade energy, an optimization based only on conventional first law analysis will not provide us with a clear picture. We need second law analysis (exergy analysis) [20] in such case.

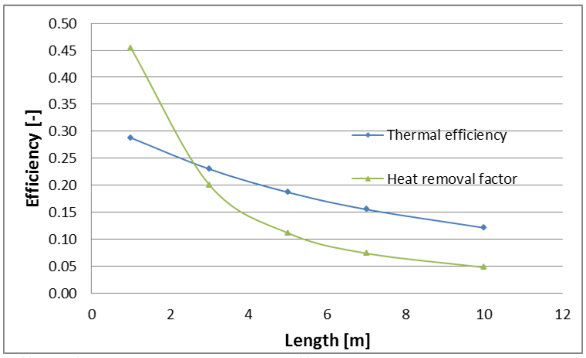

Fig. 11: Effect of PVT length on thermal efficiency and collector heat removal factor

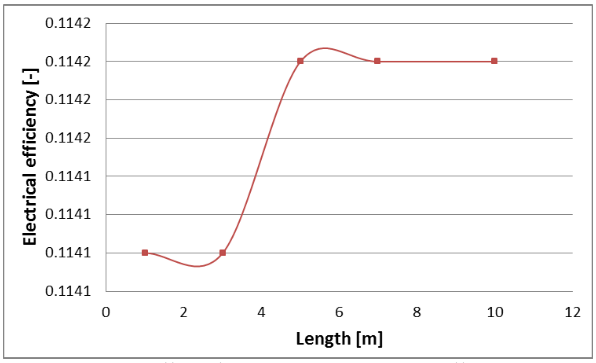

Fig. 12: Effect of PVT length on electrical efficiency

The effect of absoptance of PV surface on performance

We present the effect of PVT surface absoroptance (1 - ρ) on the PVT system. For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; solar irradiation, I= 700 W/m^2; ambient temperature, T_{amb} = 20 ˚C; $\dot{V}$ = 20 l/s per channel; wind velocity, $\dot{v}$ = 5 m/s; channel depth, d= 0.03 m; PVT length, l= 1 m.

PVT surface absorptance has opposite effect of PVT length on its performance. If we increase the PVT surface absorptance, the thermal efficiency increases (Fig. 14) but electrical efficiency decreases (Fig. 15). An optimum absorptance will also require a trade-off between electrical and thermal efficiencies.

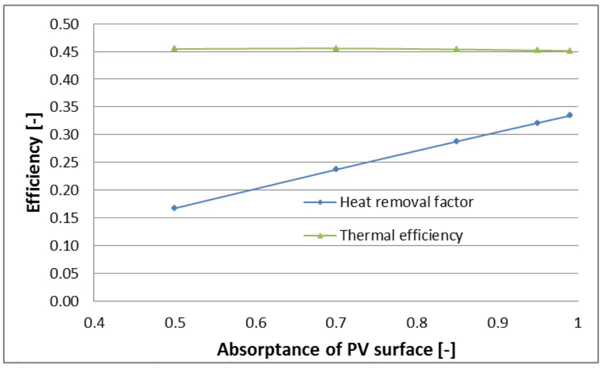

Fig. 14: Effect of absorptance of PV surface on thermal efficiency and collector heat removal factor

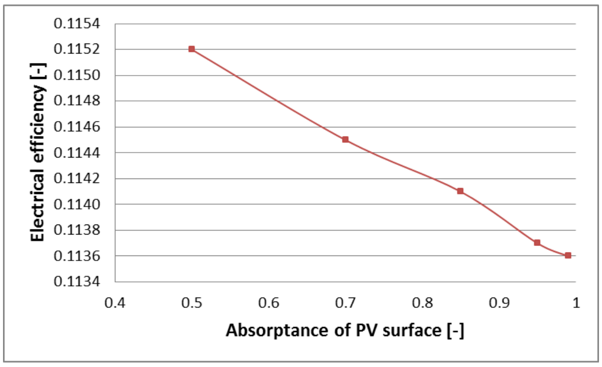

Fig. 15: Effect of absorptance of PV surface on electrical efficiency

The effect of wind velocity on performance

For this analysis we have assumed major input variables/parameters as: air inlet temperature, T_{in}= 20 ˚C; solar irradiation, I= 700 W/m^2; ambient temperature, T_{amb} = 20 ˚C; $\dot{V}$ = 20 l/s per channel; channel depth, d= 0.03 m; PVT length, l= 1 m; and reflectance of the PV surface, ρ = 0.15 (dimension less). If the wind speed is increased, the thermal efficiency decreases (Fig. 16). This is due to the fact that with higher wind speed, much of the heat from the PVT surface (which is unglazed) is lost to the environment. This cools the PV plate and consequently the electrical efficiency increases (Fig. 17). We do not have control over wind speed but this analysis suggests that where thermal energy is of higher importance, we may consider using glazed air heaters.

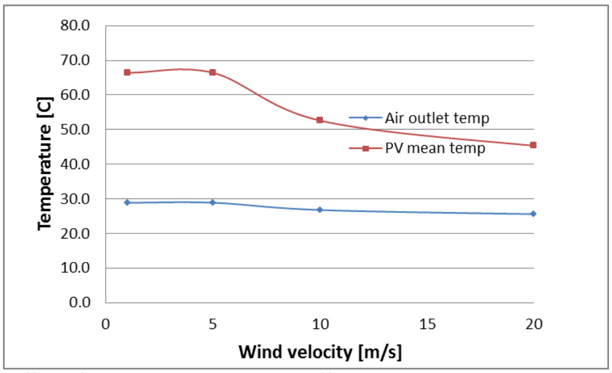

Fig. 16: Effect of wind velocity on thermal efficiency and collector heat removal factor

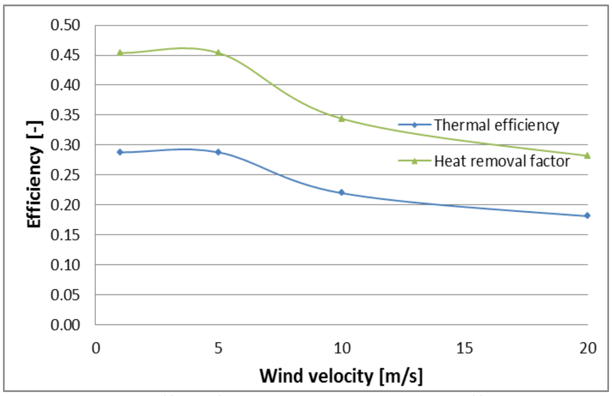

Fig. 17: Effect of wind velocity on electrical efficiency

3.2 System performance

Fig. 18 presents the simulation results of building heating load for 20 ˚C zone temperature inside the modelled building, PVT air outlet temperature and correspoinding ambient temperature and irradiation for a winterday in Sydney. In Fig. 18 the ambient temperature varied between 11 ˚C to 20 ˚C while the PVT air outlet temperature varied between 11 ˚C to 34 ˚C. The instantaneous heat load varied between 0 to 4 kW. The PVT outlet temperature remains above 20 ˚C for about 5 h (from 8 am to 1 pm) which may be used for spacingheating of modelled house at 20 ˚C. Total heat load during this period (7 am to 5 pm) was about 17 kWh (Fig. 19). With one 1x8 PVT panel about 28% heat demand can be met. However, there will be no heat available to be stored in PCM for later use. If we use three 1x8 PVT panel about 50% heat demand can be met of total heat demand from 7 am to 5 pm and the rest can be stored in PCM for later use. If we use five 1x8 PVT panel about 55% heat demand can be met of total heat demand from 7 am to 5 pm and the rest can be stored in PCM for later use.

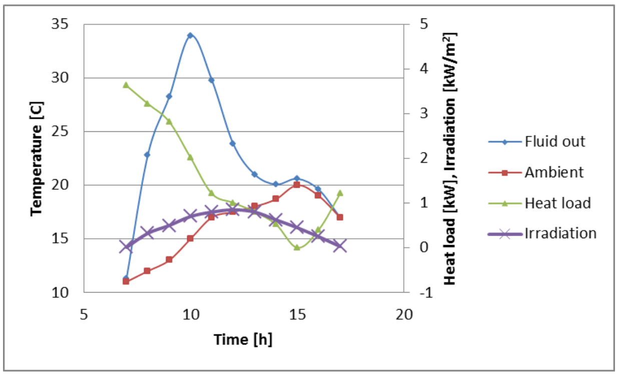

Fig. 18: Ambient temperature and irradiation on a winter day in Sydney with simulated PVT air outlet temperature

and building heating load to ensure 20 ˚C zone temperature inside a building

For building load calculation we have assumed building loss coefficient 1.4 W/m^2.K and occupancy factor 50% i.e., about 50% of the floor area was counted in heat load. The inlet air temperature to PVT system is assumed to be same as the ambient temperature. Each PVT system was assumed to be 1 m wide and 8 m long. With average effectiveness [16] 0.5, we can store about 15 kWh heat for up to 6 h in 340 kg of salthydrate PCM [17] with the assumption that average ambient temperature remains 8 ˚C. Air flow rate was assumed 300 l/s for the PCM discharge time calculation.

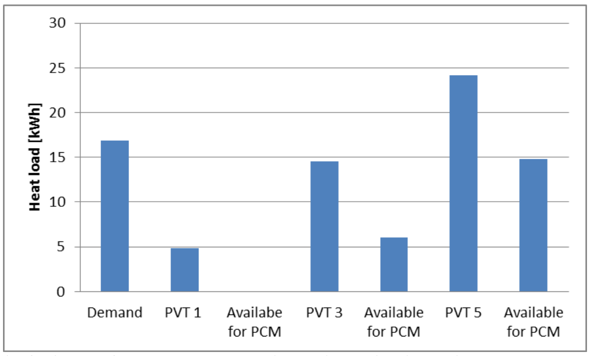

Fig. 19: Total heat load of a house from 7 am to 5 pm in a winter day in Sydney to ensure 20 ˚C zone temperature and possible energy harness from PVT (1, 3 and 5 of 1x8 m^2) with available energy for PCM to store

Fig. 20 presents discharge time vs. average heat transfer effectiveness for 15 kWh PCM heat storage with constant air mass flow at 300 l/s. The average heat trasfer effectiveness increased from 0.1 to 0.9 and the PCM discharge time decreased from 30 h to just over 3 h. One of the major issue of PCMs is the low heat trasfer rate. In Fig. 20 we can see that decreasing average heat trasfer effectiveness (or heat trasfer rate) it takes loger to discharge stored heat. This phenomenon can be useful for highly efficient and costeffective building design. We can incorporate PCMs directly into building envelope or use in a separate storage system without spending much in insulation of PCMs. Furthermore, from thermodynamic perspective since we are using thermal energy directly (no work done in the process) for energy storage in PCM, entropy generation due to heat transfer [21] may be high but first law efficiency [20] can be close to the theoretical limit.

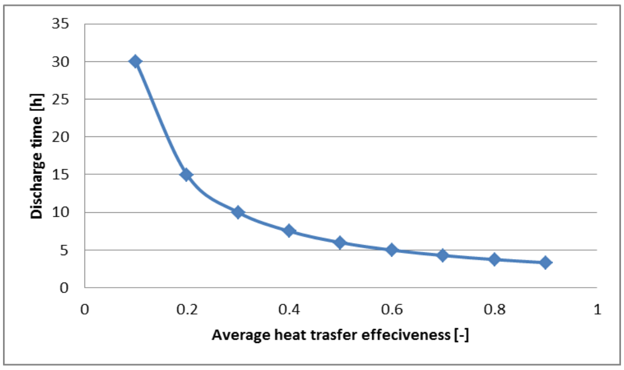

Fig. 20: Time vs. average heat transfer effectiveness of 15 kWh PCM heat storage

4 CONCLUSIONS

Air based PVT system is a promising technology to reduce space heating energy demand. Some of the parameters have more significant effect than others over performance. Increasing PVT size we can increase percentage of heat demand met from PVT. However, this increment is reduced significantly with more than 3 PVT panels. There is a tradeoff between the percentage of heat demand met from PVT with its increasing cost associated with size. We can use PCM to store the excess heat we harness during the day and use at night. The low heat trasfer rate of PCMs may be advantageous if we want to store the heat for longer time.

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