EFFECT OF USING TWO PCMS ON THE THERMAL REGULATION PERFORMANCE OF BIPV SYSTEMS

Ming Jun Huang[1] and Neil Hewitt[2]

Centre for Sustainable Technologies, School of Built Environment, University of Ulster, Newtownabbey, Co. Antrim, N. Ireland, BT37 0QB, UK
[1]m.huang@ulster.ac.uk
[2]nj.hewitt@ulster.ac.uk

Abstract

Building Integrated Photovoltaics (BIPV) is one of the most promising applications for Photovoltaics (PV). However when the temperature on the BIPV increases, the conversion efficiency deteriorates. A PV/PCM system using Phase Change Materials (PCM) for BIPV thermal control has been experimentally and numerically studied recently. One of the main barriers for this application is how to improve the low thermal conductivity of the PCM for longer thermal regulation on PV. Although the metal fins can improve the heat transfer, the effect of the thermal regulation period declined as the metal mass increased along with the decreasing thermal control period. A modified PV/PCM system integrated with two types of phase transient PCMs for improving the heat regulation need to be investigated. The performance of using PCMs with a set of different phase change temperatures is expected to improve the heat regulation on the PV/PCM system and increase the thermal regulation time. In this study a series of numerical simulations tests have been carried out in realistic conditions, and the thermal regulation of the PV/PCM system in optimised metal cells using a different range of phase transient temperature PCMs has been discussed.

1. INTRODUCTION

Building integrated photovoltaic systems (BIPVs) are widely recognised as the most cost effective form of PV power generation (NREL, 2008). As well as producing electricity, BIPV panels can replace some of the conventional wall cladding and roofing materials, therefore reducing the net costs of the PV system. The elevation of the PV temperature reduces solar to electrical energy conversion efficiency by 0.4-0.5%K^{-1} for crystal silicon PV when it rises over the characteristic power conversion temperature of 25°C (Ingersoll, 1986, Krauter et al, 1994). Maintaining the silicon PV's temperature at a low temperature, preferably lower than or around 25°C will retain the maximum conversion efficiency of the PV for practical applications. Active heat dissipation in the BIPV using air or water cooling introduces the cost of pumping and increases system maintenance. Passive cooling by natural, wind induced air convection in a duct behind the PV is commonly used in BIPV systems. Tonui and Tripanagnostopoulos (2007) and Fossa et al. (2008) studied the improvements in natural ventilation for PV façade by suspending a group of fins in the air channel, inserting the fins and selecting the distance between the air duct walls. An experimental analysis of a naturally ventilated PV with metal fins to form an opening channel behind the PV was carried out by Huang et al. (2006a). The results showed that a maximum 47°C temperature on the front surface of the PV system could be achieved in ambient temperature 23±1°C and insolation 750W/m^{-2}. However, the poor heat transfer properties of air when only subject to natural convection limit their ability to maintain the optimum operating temperature for the PV panels during the peak time applications.

An investigation of a system which uses PCMs to absorb energy as latent heat at a constant phase transition temperature and to regulate the rise in PV temperature (PV/PCM) has been carried out recently (Huang et al., 2004, 2006a, 2006b, 2007 and 2008). These studies used paraffin wax-based PCMs with different forms of phase change (solid-liquid and solid-solid) to determine the optimal properties for PV temperature regulation. Using the PV/PCM system with single PCM RT25 the temperature on the PV could still reach as high as 38°C during the phase change, although this was 18°C less than compared with the plain PV panel (56°C) in the same ambient conditions (Huang et al, 2006a). During crystallisation the cavity formed between the body and the surface of the PCM can increase the thermal resistance further (Huang et al., 2008). The further study on using different type of PCMs: eutectic mixture of capric-lauric acid (C-L) have been carried out (Hasan et al., 2008).

A series of arrangements with different types of fins inside of the PV/PCM system was also carried out. The metal fins can reduce the temperature rise in the PV. Although the metal fins can improve the heat transfer, the thermal regulation period declines as the metal mass is increased with the thermal control capacity increasing. The performance of using PCMs with a set of different phase change temperatures is expected to improve the heat regulation on the PV/PCM system and increase the thermal regulation time. To this end, a modified PV/PCM system has integrated with two different phase transient PCMs. A series of numerical simulations tests have been carried out in realistic conditions. The thermal regulation of the modified PV/PCM system in optimised geometry cells using a different range of phase transient temperature PCMs has been discussed in this paper.

In the PV/PCM system, the positions of the two PCMs along with the container shape are important for the thermal regulation of the system. A good understanding of the fundamental heat transfer processes involved is essential for accurately predicting the thermal performance of the PV/PCM system and for avoiding costly system design mistakes. The complexities of the processes include (a) the nonlinear motion of the solid-liquid interface within the PCM; (b) the presence of buoyancy driven flows during the melting process; (c) the volume expansion of the PCM, and (d) the density change in the PCM that ensues during melting/solidification (Dincer and Rosen, 2002).

Simulating the behaviour of the PV/PCM system with the two different phase transient temperature PCMs in real thermal applications is subject to the cyclic melting and solidification boundary conditions. In this simulation, the insolation and ambient temperatures for the south-east (SE) of England with SE orientation on 21stJune when the insolation was greater than 120 Wm^{-2} are considered as three day input data for the ambient conditions along with the geometrical conditions.

The simulating model used in this work is based on a two dimensional temperature-based finite volume numerical model to moderate the temperature rise of building integrated photovoltaic (PV) in a PV/PCM system. This model has been developed and experimentally validated by the authors (Huang et al., 2004). A brief summarization is as follows.

An energy balance in a PV/PCM system for unit surface areas can be written as:

$$\tau\alpha I_T \Delta t = \eta_c I_T \Delta t + U_L \left(T_{PV} - T_{amb}\right)\Delta t + Q_S \quad (1)$$

The triangular shape is good for releasing the bubbles produced during the melting process therefore easing the volume expansion which challenges many PCM applications. Assuming that the change in the volume of PCM in liquid states is negligible and that the initial temperature is T_{amb}, the energy stored in the system is:

$$\left.\begin{array}{ll} Q_s = mc(T_{PV} - T_{amb}) & T_{amb} < T_{PV} < T_m \\ Q_s = mc(T_m - T_{amb}) + H & T_m \le T_{PV} < T_m + \Delta T \\ Q_s = mc(T_m - T_{amb}) + H + mc(T_{PV} - T_m) & T_{PV} \ge T_m \end{array}\right\} \quad (2)$$

2. DESCRIPTION OF THE MODELLED PV/PCM SYSTEM

The three most significant thermal characteristics of affecting the performance of the PV/PCM system are the PCM heat capacity, the phase change temperature and the location of the PCM and mass in the system. These parameters as well as others characterise the PV/PCM system and affect thermal regulation therefore PV conversion efficiency. In this paper, the PV/PCM system has been designed with small metal cells to hold two types of PCMs considered to enhance heat transfer. The schematic of the PV/PCM with metal cells is illustrated in Figure. 1. The incident energy I_T absorbed by the PV as heat is conducted through the high heat transfer cell wall to the PCM and dissipated from the rear of the PV/PCM system. The different thermal regulation characters of the PCMs can hold the PV temperature at lower levels for longer periods. The PCMs that are commercially available with different phase transient temperatures from 21 to 60°C are combined to regulate the PV temperature rising in the PV/PCM system. Different combinations of the PCMs used to augment the PV/PCM system are analysed for realistic diurnal temperature and insolation boundary conditions in the England summer period and the heat transfer and temperature distribution are predicted. The thermal properties of the four PCMs that can be combined into the types of PCMs from RUBITHERM [Anon, 2009] used as input data in the simulations are presented in Table 1.

Table 1. Thermophysical properties of RT21, RT27, RT31 and RT60 (Anon, 2009)

		RT21	RT27	RT31	RT60
Property	Melting temperature	21	27	29	60
	Latent heat (kJ/kg)	134	184	169	144
	Density (kg/l)				
	Liquid	0.76	0.75	0.77	0.78
	Solid	0.84	0.84	0.89	0.95
	Thermal conductivity (W/mK)	0.2	0.2	0.2	0.2
	Viscosity (mm^2/s)	25.71	26.32	28.57	37.05

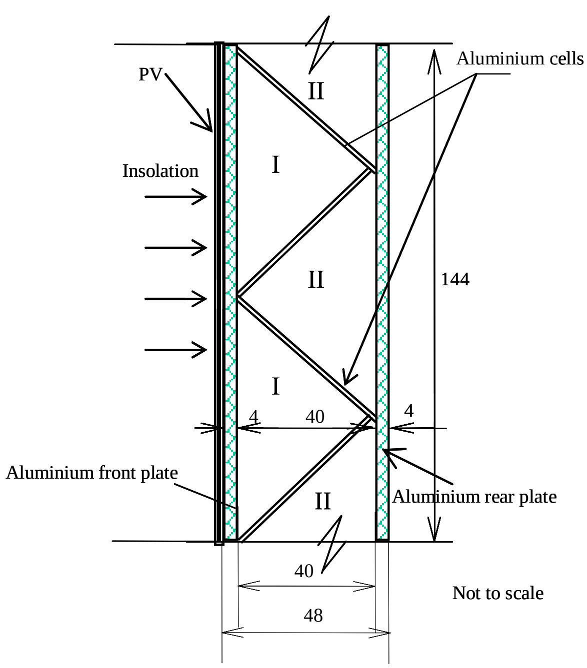

Fig. 1. Schematic diagram of PV/PCM system with metal cells for different PCMs

The heat transfer coefficients from the front and back surfaces of the PV/PCM system are set at 10 $Wm^{-2}K^{-1}$ and 5 $Wm^{-2}K^{-1}$ (to simulate natural ventilation conditions) and the top and bottom boundaries of the system are assumed to be adiabatic. The air inside of the cells is assumed to be still. A grid of 1mm square finite volumes and a variable time step with a minimum value of 0.0125 s are used for all the simulations.

To predict long term temperature control, three days are simulated using weather data for the 21st June for the SE of England on the vertical south-east oriented PV/PCM system. For the simulations, realistic ambient temperatures and insolation boundary conditions are regarded as invariant over 5 minute intervals. The simulation temperatures within the PV/PCM system are all initially set to the outdoor ambient temperature at 00:00 hr for the transient applied boundary condition.

3. PARAMETRIC ANALYSIS

In order to evaluate the PV/PCM performance, predictions of the temperature development with the two phase materials, a single PV plate is predicted as a reference for performance comparison. The predicted reference temperature is at 68.45°C with insolation 1000 W/m^2 and ambient temperature 20°C. The following five cases in which using the two PCM combinations have been simulated on setting conditions of insolation 1000 W/m^2 and ambient temperature 20°C and three days ambient conditions:

- RT27 with air cell
- RT27 with RT21
- RT27 with RT27
- RT31 with RT27
- RT60 with RT21

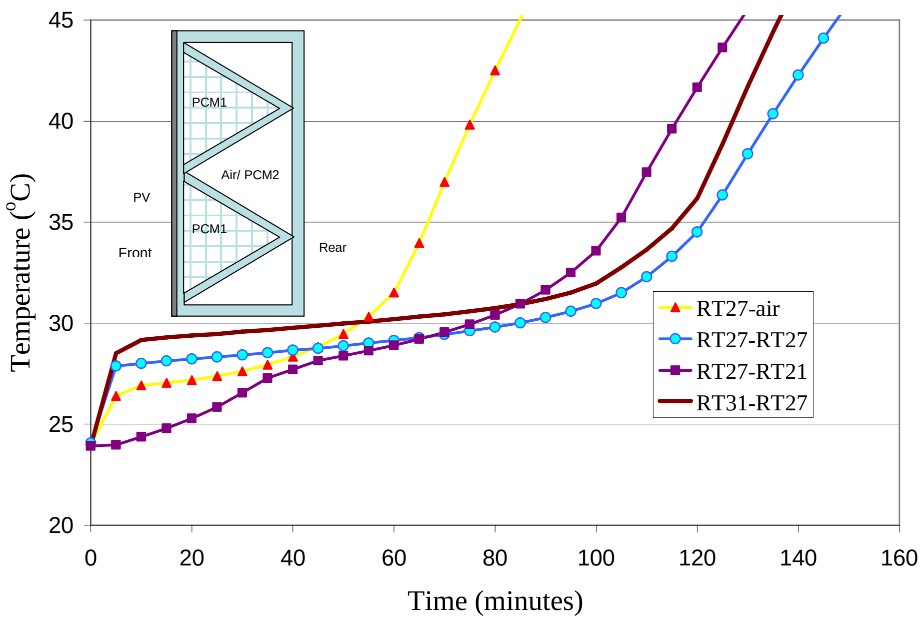

Figure 2. Comparison of front surface temperatures evolution predicted for four cases of the PV/PCM system with insolation of 1000Wm^{-2} and an ambient temperature of 20°C

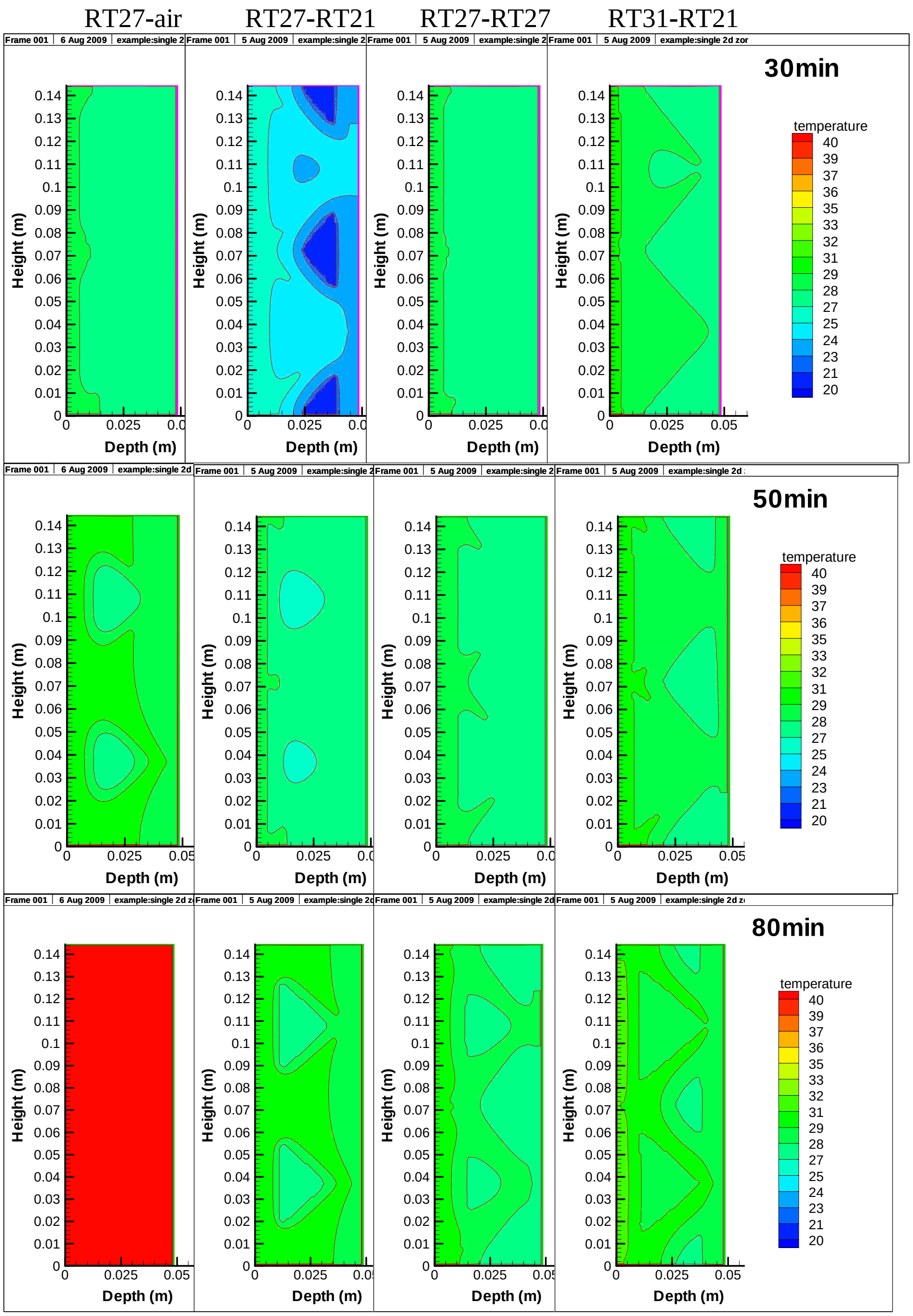

Figure 3. Predicted isotherms for the PV/PCM system with four cases of RT-air, RT27-RT21, RT31-RT27 during the PCM phase change process

Figure 2 shows the predicted temperatures on the front surfaces of the PV/PCM system for an insolation 1000W/m^2 and ambient temperature 20°C. The insolation absorbed on the front surface of the PV/PCM system and conducted through the PV increases the temperature of the metal cell wall. The metal wall of the cell provides good thermal transfer to the two PCMs. As time elapsing, it can be seen that the temperature on the front surface of the PV/PCM system has a lower temperature rise for the system with case RT27-air than that with the RT27-RT27 full filled system, and the thermal regulation period is shorter. It is easy to understand that the air cell can have better heat transfer compared with the lower thermal conductivity of RT27. This also can be observed from the predicted isotherms for the PV/PCM system cross-sections as shown in Figure 3. At the first 30 minutes the temperature inside of the system with RT27-air is relatively more uniform than the RT27-RT27 case. After 60 minutes the front temperature on RT27-air increases more rapidly to the insolation intensity than the RT27-RT27 system does, and the thermal regulation period is only less than half of the case RT27-RT27. The thermal distribution on the RT27-air case tends to be more uniform than other cases (see Figure 2 and 3). The position of the PCMs is an important factor on thermal regulation. When combined with low phase change transient PCM the temperature on the front surface of the PV/PCM system has a lower temperature rising.

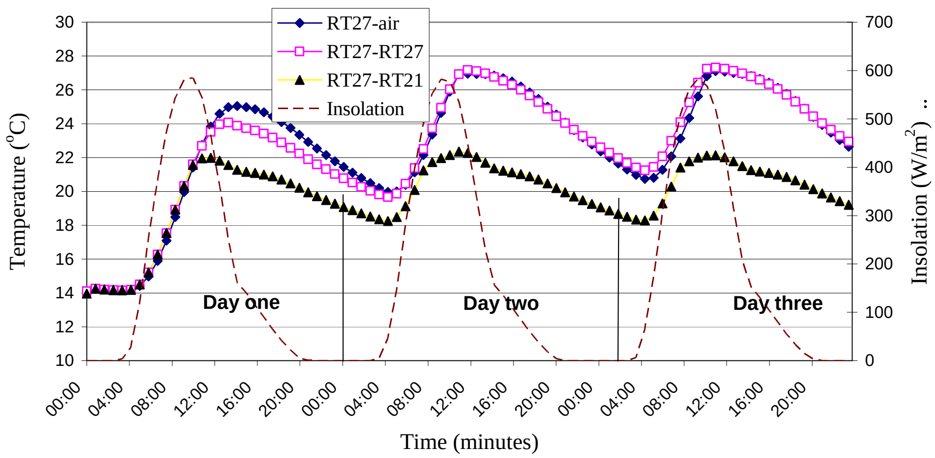

Figure 4 Averaged temperature evolution at the front surface of the PV/PCM system with the different PCM combinations for a three day simulation using the weather data on 21st of June SE England

A three day simulation using the weather data on 21st of June has been undertaken to predict the heat accumulation in the PV/PCM system with a combination of two PCMs and is presented in Figure 4. The temperatures of the system respond more rapidly to the insolation than to the ambient temperatures. When no insolation is involved, it can be found that the temperature on the front surface of the system decreases with phase change properties. The temperature of the PV/PCM systems follows the incident insolation but lags with the properties of PCMs by more than 20 minutes. Absorbed solar energy is stored in the PCMs during high daytime temperatures and subsequently released to the ambient in the evening. The predicted temperatures for the second and third days for all the cases are the same, the PCM has thus released all its latent heat to the ambient environment at night and returned to its solid phase at the start of each period of insolation. For the RT27 PCM a full transition to the molten state has not been achieved. There is no significant difference between RT27-RT27 and RT27-air. For these cases the thermal regulation on the PV can be gained by reducing the depth of the PCM RT27 to beyond 30 mm. The RT27-RT21 case can efficiently control the temperature on the PV under 22°C for the whole test period. The phase change transient with RT21 can be seen more clearly during the cooling (see Figure 4). For two different PCMs the lower phase transient one dominates the whole system performance. The same situation can be seen from the RT31-RT27 and RT60-RT21 combination case as illustrated in Figures 5 and 6. The phase transient performance is clear on the cooling stage.

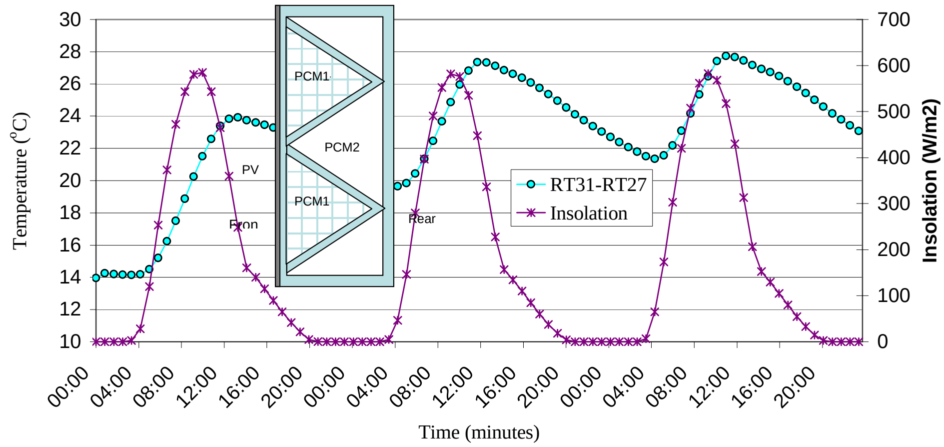

Figure 5 Averaged temperature evolution at the front surface of the PV/PCM system with the PCM RT31 and RT27 combination for a three day simulation using the weather data on 21st of June SE England

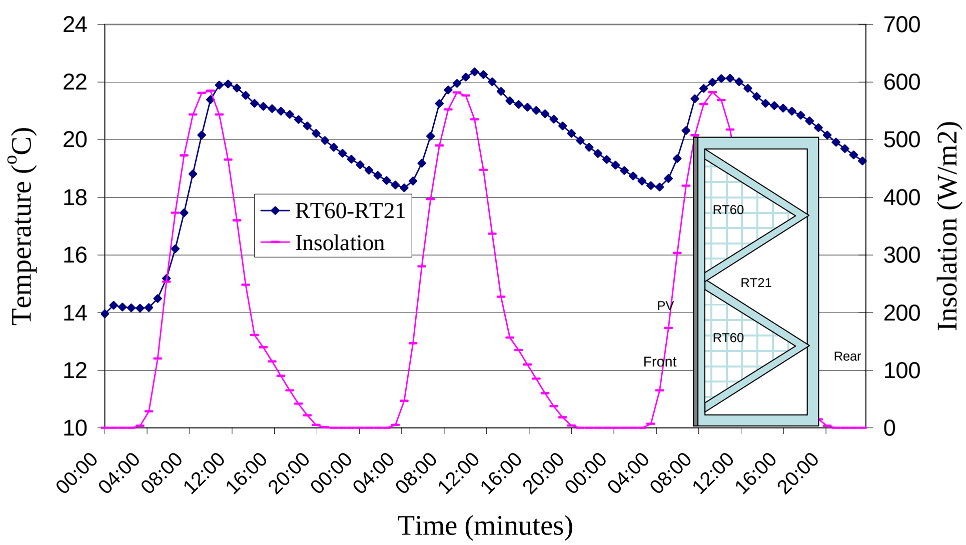

Figure 6 Averaged temperature evolution at the front surface of the PV/PCM system with the PCM RT60 and RT21 combination for a three day simulation using the weather data on 21st of June SE England

The convection effect on the heat transfer inside of the two phase materials of the PV/PCM system is ignored in this paper due to the small size of the cells used to hold the PCMs and the temperature range during the process is narrow. A preliminary study on the effect of convection has been explored (see Figure 7). More detailed discussions will be presented in the future.

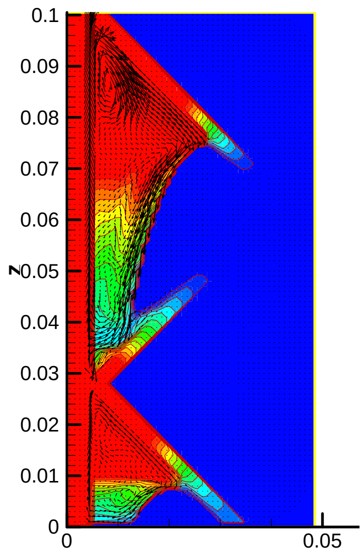

Figure 7 Predicted isotherms and velocity vectors diagrams for cross-sections of the PV/PCM system when exposure to insolation 1000 Wm^{-2} and the ambient temperature at 20°C

4. CONCLUSION

The PV/PCM system with two types of PCMs can maintain the PV at operating temperature closer to its characteristic value of 25°C and thus lead to an improvement in solar-to-electrical conversion efficiency under variable diurnal insolation. The incident energy I_T absorbed by the PV as heat is conducted through the high heat transfer cell wall to the PCMs and dissipated from the rear of the PV/PCM system. The different thermal regulation characters of the PCMs can keep the PV temperature at lower levels for longer periods. The PCMs evaluated at different combinations show that the thermal regulation performance of the PV/PCM depends on the thermal mass of PCMs and the thermal conductivity of both the PCMs and the PV/PCM systems. Comparing different combinations, RT27-RT21 achieves the highest temperature reduction during the daily operation. Compared with the previous PV/PCM systems (Huang et al. , 2006a), the system with triangle cells can ease the volume expansion and extend the thermal regulation period.

NOMENCLATURE

c	Specific heat capacity	$Jkg^{-1}K^{-1}$
m	Mass	kg
ΔT	Transition temperature of PCM	°C
T_{PV}	PV Temperature	°C
T_{amb}	Ambient temperature	°C
T_m	PCM Melt temperature	°C
Q_S	Energy stored in the system	Jkg^{-1}
H	Latent heat capacity	Jkg^{-1}
I_T	Insolation incident on photovoltaic cell	Wm^{-2}
h	Heat transfer coefficient	$Wm^{-2}K^{-1}$
η_c	PV Electrical conversion efficiency	
τ	Transmittance of PV cover	
α	Absorptance of PV	
U_L	Overall heat loss coefficient,	$Wm^{-2}K^{-1}$
Δt	Time step	s

5. REFERENCES

Anon, RUBITHERM data sheets for RT21, RT27, RT31 and RT60, RUBITHERM GmbH, Schumann company. (2009).

CIBSE, Student Members Data Book, Second edition, Chartered Institute of Building Services Engineers, London, UK. (1991).

Dincer I. and Rosen M.A., Thermal Energy Storage, John Wiley & Sons, Ltd, England, pp. 303-335, 2002.

Hasan, A., McCormack, S. J., Huang, M. J., Norton, B., (2008). Phase change materials for thermal control of building integrated photovoltaics: characterization and experimental evaluation. Proceedings of the 4th Photovoltaic Science, Applications and Technology Conference (PVSAT-4), April 2nd – 4th, Bath, UK, pp. 105-108.

M.J. Huang, S.McCormack, P.C. Eames and B.Norton, (2008), The Effect of Phase Change Material Crystalline Segregation on the Building Integrated Photovoltaic System Thermal Performance, WREC X, Glasgow.

M.J. Huang, P.C. Eames and B. Norton, (2007), Comparison of predictions made using a new 3D phase change material thermal control model with experimental measurements and predictions made using a validated 2D model, International J. Heat Transfer Engineering, Volume 28(1), pp. 31-37.

M.J. Huang, P.C. Eames and B. Norton, (2006a), Experimental Performance of Phase Change Materials for Limiting Temperature Rise Building Integrated Photovoltaics, Journal of Solar Energy, 80, pp. 1121-1130.

M.J. Huang, P.C. Eames and B. Norton, (2006b), Comparison of a small scale 3-D PCM thermal storage model with a validated 2-D Thermal model, J. Solar Energy Materials and Solar Cells, 90, pp. 1961-1972.

M.J. Huang, P.C. Eames and B. Norton, (2004), Thermal Regulation of Building-Integrated Photovoltaics Using Phase Change Materials, International Journal of Heat and Mass Transfer, 47, Pages 2715-2733

NREL, 2008, National Renewable Energy Laboratory, A National Laboratory of the US Department of Energy Office of Energy Efficiency & Renewable Energy, http://www.nrel.gov/pv/building_integrated_pv.html.

Ingersoll J. G., (1986). Simplified calculation of solar cell temperatures in terrestrial photovoltaic arrays. ASME J. Solar Energy Engineering 108, 95-101

Krauter S., Hanitsch R. and Wenham S. R., (1994). Simulation of thermal and optical performance of PV modules, Renewable Energy, 5, 3, 1701-1703