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Effect Of Natural Convection And Thermal Storage System On The Electrical And Thermal Performance Of A Hybrid PV-T/Pcm Systems

Jurabek Abdiyev[1], Mamarajabova Aziza[2], Nigora Abdiyeva[3]

[1]Physical-technical Institute of NPO "Physics – Sun" of Uzbekistan Academy of Sciences Uzbekistan, Tashkent, Chingiz Aitmatov street 2B.
[2]Samarkand State University, Samarkand 140104, Uzbekistan
[3]Samarkand State Institute of Foreign Languages. Samarkand, 140104, street Bustonsaroy 93
Author: fiztexabdiev@gmail.com (J. Abdiyev)

Abstract: *Waste heat management is one of the prominent method of increasing the electrical performance of photo-voltaic (PV) panels by decreasing its operating temperature. In this paper, investigation on integrating natural convection phenomena with phase change materials (PCM) beneath the PV panel for heat extraction from the panel has been reported. The PV temperature is regulated by PCM and increase its efficiency. A numerical model was developed for this PV-T/PCM system and validated with the experimental data. A comparative numerical study has been performed to analyze the electrical and thermal characteristics of PV, PV/PCM and air integrated PV-T/PCM system with an incident solar radiation of 800 W/m^2. A drop of 25% and 35% has been observed in PV cell temperature for PV/PCM system and air PV-T/PCM respectively with reference to base PV system. As a result of this temperature drop the electrical efficiency of PV cell has been augmented by 14.12% and 19.75% for PV/PCM system and air PV-T/ PCM respectively.*

Keywords: Air-flow channel, Natural convection, PV Cell, PV cell temperature, Phase change materials, Electrical Efficiency.

1. INTRODUCTION.

Photo-voltaic (PV) system converts solar energy into electrical energy. However, in the process, a part of solar energy is converted into unwanted heat energy. This waste heat increases the temperature of the PV panel and deteriorates its electric conversion efficiency. Crystalline and amorphous silicon cells exhibit a drop of 0.5% and 0.25% in electrical efficiency per degree temperature rise respectively [1]. Hence electrical performance of PV panel can be enhanced by extracting this waste heat and utilizing it for some other purpose. The thermal management of PV panel also called PV thermal (PV/T) constitute regulating the PV temperature by removing this excess heat [2]. Attaching suitable phase change materials (PCM) on the back plane of PV panel is one of the prominent methods to store this excessive heat and use it during night hours [3]. PCM first absorbs heat sensibly up to the phase-transition temperature, and afterwards absorbs latent heat during phase change. During melting process, the temperature of PV panel reduces substantially. However, the heat extraction rate of PCM reduces as melting front reaches the right wall of PCM enclosure [4–5], which again leads to increase the PV panel temperature. This disadvantage of PV/PCM systems can be minimized by circulating a secondary fluid above or beneath the PV panel to remove this extra amount of heat to lower its temperature further.

Addition of secondary fluid flow to PV/PCM system makes it PV-T/PCM system [6]. Water could be a good secondary fluid due to its high heat capacity and density but it consume considerable amount of power for circulation [7–9]. Air on the other hand has very low specific heat but can be a good coolant at higher mass flow rate. However to achieve these higher mass flow rate a considerable amount of external power is required which decreases the net power output of PV-T/PCM system. Furthermore air at low and moderate mass flow rate consumes power which significantly reduce net power output of the system as air is circulated by forced convection through the system. Circulation of air shows considerable enhancement in electrical and thermal performance of PV-T/PCM systems [10]. Therefore, in the current study our aim is to eliminate this disadvantage of external consumption of power for air circulation with insignificant compensation in electrical performance of PV panel.

Power consumption for pumping the fluid in the system can be eliminated altogether is forced convection system is replaced by natural convection. A natural convection system works on buoy

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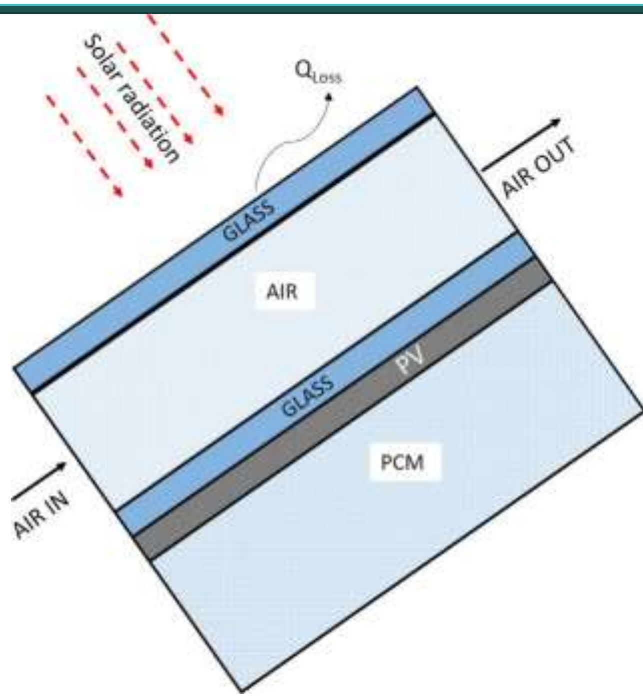

Fig. 1. Schematic diagram of natural air-flow PV-T/PCM system.

ancy principle wherein air flow due to changes in density. As shown in the schematic Fig. 1, radiation penetrate the glass and heats the PV panel. A part of the energy is converted into electrical energy and part of energy which is converted into heat is taken away by air from the top and PCM from the bottom. Air in the top channel gets heated from the PV panel and convection current sets in that absorb a fraction of heat. Due to heat extraction by the air and PCM, the overall electrical efficiency of PV panel increases. In this paper, effect of heat transfer from both the sides of PV has been investigated. Since the developed numerical model handle both natural convection and melting of PCM, the model is validated with the experimental data of natural convection and melting of PCM. Effect on PV-T/PCM performance due to convection and PCM melting has been discussed separately and compared with the base configuration. Overall, about 20% increase in PV panel efficiency was observed in PV-T/PCM system.

2. NUMERICAL MODEL AND METHODOLOGY.

Two dimensional numerical model is being created to study the behavior of PV panel when natural air flow channel is attached above PV panel and PCM enclosure beneath the PV panel. Length of the domain is considered 200 mm and thickness of air flow channel and PCM enclosure is considered to be 20 mm each. The thickness of glass and PV panel is considered 3 mm and 1 mm respectively. A comparative numerical analysis of performance of PV panel is carried out with air-flow channel and PCM enclosure both, with PCM enclosure only, and with PV panel only under the solar radiation of 800 W/m^2. Air PV-T/PCM system is inclined 25L to horizontal as per latitude of Varanasi. OM32 is used as PCM and its thermo-physical properties is given in Table 1. PCM exhibit same thermos-physical properties independent of phase change and temperature. Density is supposed to vary with temperature only in gravity force term to compensate buoyancy force term according to Bossiness approximation.

Solar radiation is incident on the top glass layer and transmitted to PV panel through air flow channel, which after converting a part of this radiation into electrical energy. Remaining amount of energy is transmitted to PCM and air by both convective and conductive manner from each side of PV panel. The convective and radiative losses from the top surface are being taken care of by assigning the heat transfer coefficient h ¼ 5:7 þ 3:8v_1 W/m^{2}K to the top glass layer, environmental wind velocity (v_1) is assumed to be zero for standstill condition. All other walls are considered to be well insulated.

2.1. METHODOLOGY.

The computational domain consists of four different regions: air, glass, PV cell and PCM. Conductive heat transfer is dominant in glass and PV cell region whereas, heat transfer in air and PCM region is controlled by both conduction and convection. Following assumptions have been made regarding air and PCM regions: (a) both are incompressible and Newtonian fluid, (b) no-slip condition on the side walls of air region and all inner walls of PCM region, (c) pressure at outlet of air region is equal to atmospheric pressure, (d) viscous heating is absent, (e) laminar fluid flow, (f) PCM has same thermo-physical properties for solid and liquid phase with constant melting temperature, and (f) Bossiness approximation.

Mass conservation equation:

where S is source term which consist of two terms for PCM layer while for air channel source term consists of only Bossiness term. The Bossiness term is the gravity force term to consider the effect of buoyant forces. Darcy term controls the transition of solid phase to liquid phase at solid–liquid interface of PCM. The mushy constant C exhibit a steeper transition at higher value (10^8 – 10^9), whereas at lower values of C solid phase enact as highly viscous fluid. Hence for current investigation a higher value of C (10^9) is chosen. To avoid numerical error (division by zero), a very small constant e (0.0001) is added in denominator of Darcy term as liquid fraction (f_l) tends to zero initially.

Energy conservation equation:

The energy conservation equation for liquid PCM and air region can be written as:

The second term on the right hand side of Eq. (3) is valid for PCM region only. This term represents the latent heat absorption during melting phase change. This term is not considered for air flow channel in the Eq. (3). Moreover, the energy equation for PV cell and glass region can be written as:

The terms P_{out} (volumetric source term due to power generation by PV cell) and Q_{gen} (volumetric source term due to absorbed solar radiation by PV cell) in Eq. (4) are valid only for PV cell region only. These volumetric source term can be evaluated as:

The electrical efficiency (g_{pv}) of PV cell depends on its temperature. The relation between PV cell temperature and electric efficiency is suggested by Evans et al. [12] as equation: where the subscript 'ref' describes the reference operating condition of PV cell. For the current study, c-Si type PV cell is analyzed with reference operating condition as T_{ref} ¼ 25 C, g_{ref} ¼ 0:124, and b_{ref} ¼ 0:00392 1=K respectively. The transmissivity of the glass (s_{glass}) and absorptivity of PV panel (a_{pv} Þ are 0.95 and 0.9 respectively [13].

Conservation equations are discretized using finite volume method with implicit stepping scheme. The pressure velocity link-age has been solved by using SIMPLER scheme. Power law scheme is used to calculate coefficient of algebraic discretized equations. A time step of 0.05 s is selected for the numerical investigation. Con-vergence in inner iteration is calculated on basis of relative error and overall energy balance. It must be with in allowable limits.

For grid independency test, the centerline temperature along the length of PCM and air region at 3600 s is calculated. Simulations are performed with 29 100, 41 133, 53 200, and 65 267 grids for both regions. Relative error of 0.3% is predicted for 53 200, and 65 267 grids. Based on these predictions 53 200 is adapted for optimum settlement of resolution and CPU time.

2.2. VALIDATION OF METHOD.

For validation of developed numerical model, a set of numerical simulation has been carried out. In first simulation flow through air-flow channel is validated with experimental study done by Cheng and Muller [14]. A numerical two dimensional model exact similar to experimental set up is considered. The variation of temperature profile across width of channel have been analyzed with numerical and experimental results as shown in Fig. 2(a). The temperature profile obtained using results shows good agreement with experimental results.

In second simulation melting in a rectangular PCM enclosure is validated with the experimental study done by Kamkari et al. [4]. A two dimensional model exactly similar to experimental set up is developed. Variation of liquid fraction with time have been com-pared with numerical and experimental results as shown in Fig. 2(b). The plot obtained by numerical results shows a good agreement with experimental findings.

3. RESULTS AND DISCUSSIONS.

3.1. SOLID-FRACTION AND TEMPERATURE DISTRIBUTION CONTOURS.

Fig. 3(a) depicts the solid fraction contour for (i) PV/PCM system, and (ii) Air PV-T/PCM system at 120 min. Melting in PCM region is dominated by conduction initially. This conduction regime ends very soon due to formation of natural convection cur-rent with the dominance of buoyant forces in liquid PCM. Convective melting promotes the unsymmetrical melting in PCM enclosure and faster melting rate is observed in top side of cavity. Solid PCM starts to shrink along the right wall of enclosure as melting front approaches the right wall. Melting rate starts to diminish in this regime of melting. As a consequence, thermal stratification is developed within the enclosure with higher temperature at top

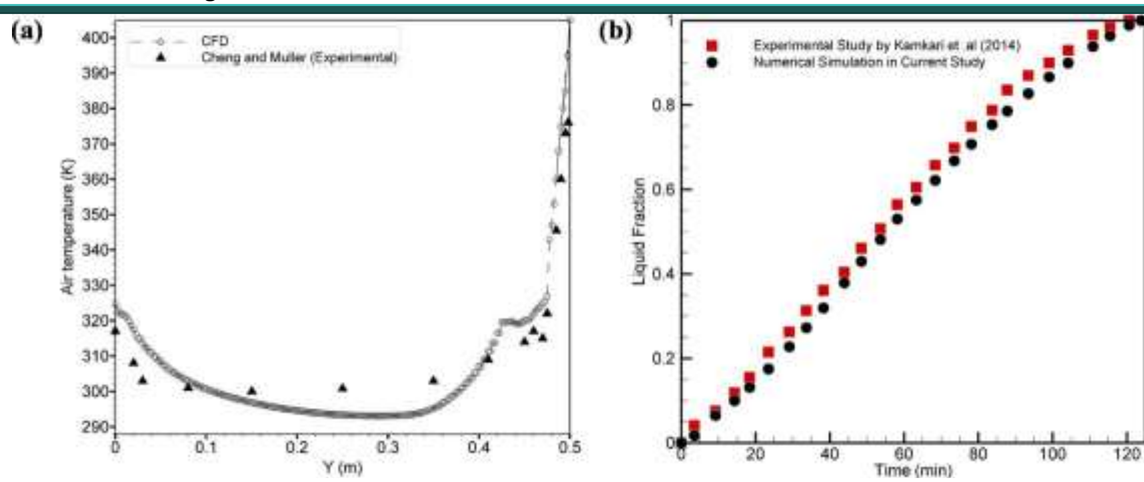

Fig. 2. (a) Comparison of temperature profile variation for numerical simulation and experimental findings by Cheng and Muller [14]. (b) Comparison of liquid fraction variation with time of numerical simulation and experimental results by Kamkari et al. [4].

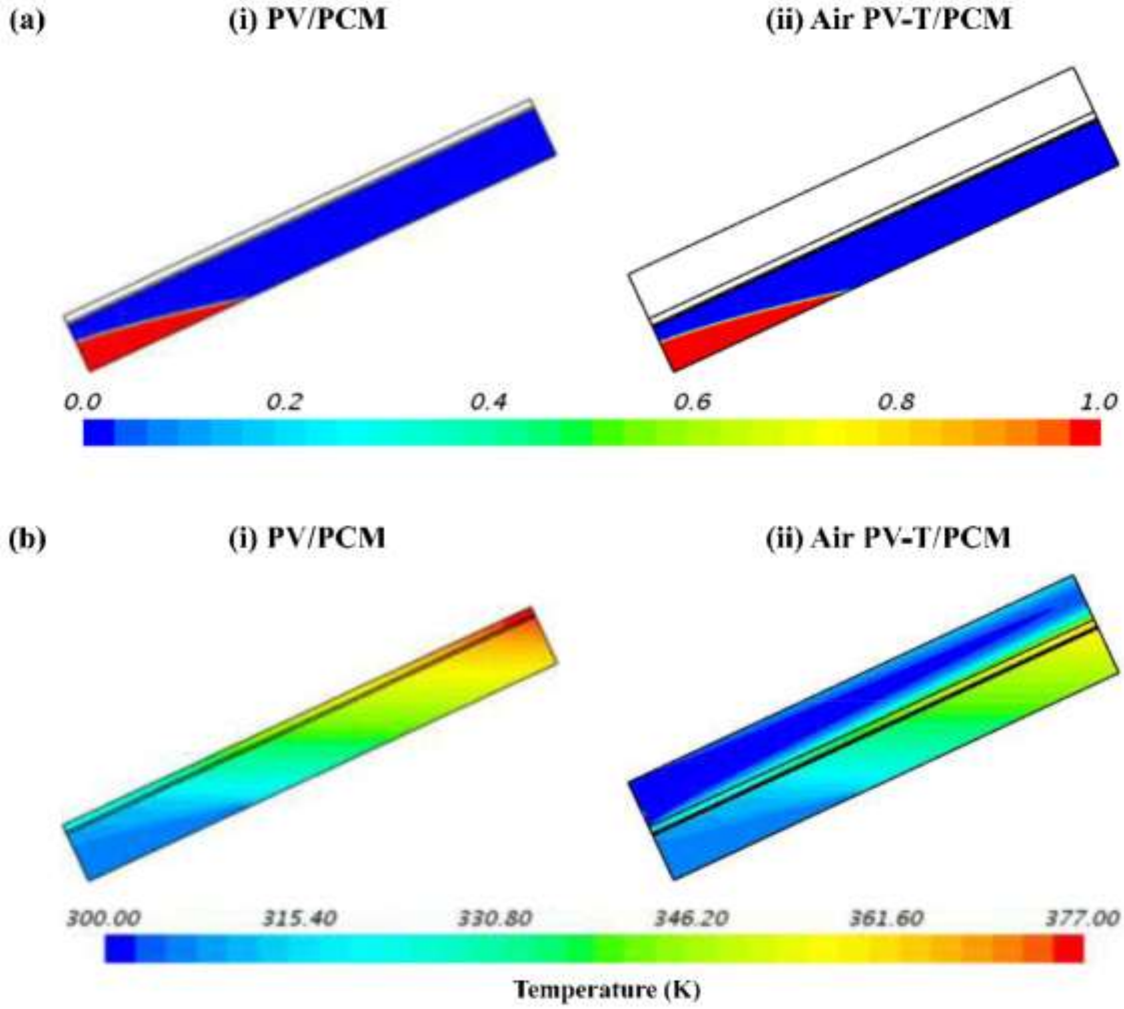

Fig. 3. (a) Solid fraction contour of (i) PV/PCM system, and (ii) Air PV-T/PCM system. (b) Temperature distribution contour of (i) PV/PCM system, and (ii) Air PV-T/PCM system.

side and lower temperature at the bottom side of enclosure. Temperature contour is shown in Fig. 3(b) for (i) PV/PCM system, and Air PV-T/PCM system at 120 min. In PV/PCM system temperature of PV panel rises up to 376 K in top side due to thermal stratification. Addition of air flow channel reduces this temperature to 358 K by extracting this excessive heat with the aid of free convective flow of air on the top of PV panel. The distribution of temperature is more uniform in air PV-T/PCM system due to smaller

Akshayveer et al. thermal stratification. Thus air PV-T/PCM system works more efficiently compared to PV/PCM system and PV system.

3.2. PV CELL TEMPERATURE.

Fig. 4 represents PV cell temperature variation with time for all the configuration i.e PV only, PV/PCM and Air PV-T/PCM systems. When exposed to a solar radiation of 800 W/m^2, PV cell temperature rises to 97.24 LC when no air-flow channel and PCM enclosure is adhered to PV panel. Attachment of PCM enclosure reduces its temperature up to 73.97 LC because it absorb more heat as latent heat. Further attaching the natural air-flow channel on top of PV/PCM system reduces its temperature to 63.24 LC. A decrease of 25% is observed in PV/PCM system and of 35% in air PV-T/PCM system when compared to PV system without any attachment.

3.3. PV CELL EFFICIENCY.

The variation of PV cell efficiency with time for all configuration is shown in Fig. 5. Initially the efficiency starts to decrease rapidly as temperature of PV cell rises due to excessive waste heat. Efficiency of PV panel reduces to 8.85% when no attachment is added to PV panel. With the attachment of PCM enclosure the some of this waste heat is absorbed by PCM and temperature of PV panel drop by a huge amount which increase the efficiency of PV panel up to 10.1%. An increment of 14.12% is observed when compared to no attachment case. Further adding air-flow channel on the top of PV panel drops down the temperature of PV cell which increases the efficiency up to 10.6%. An increment of 19.75% in electrical conversion efficiency of PV panel is observed for air PV-T/PCM system as compared to PV system.

3.4. MELTING RATE.

Melting in PCM enclosure is initially dominated by conduction due to viscous forces of liquid PCM. After sometime viscous forces are dominated by buoyancy forces due to gravity and hence, con-vective heat transfer governs the melting in PCM. This convective heat transfer is being diminished as melting front approaches the right wall. As convective heat transfer starts to diminish the melting become slower in enclosure and temperature of liquid PCM begins to rise due to more absorption of sensible heat as compare to latent heat.

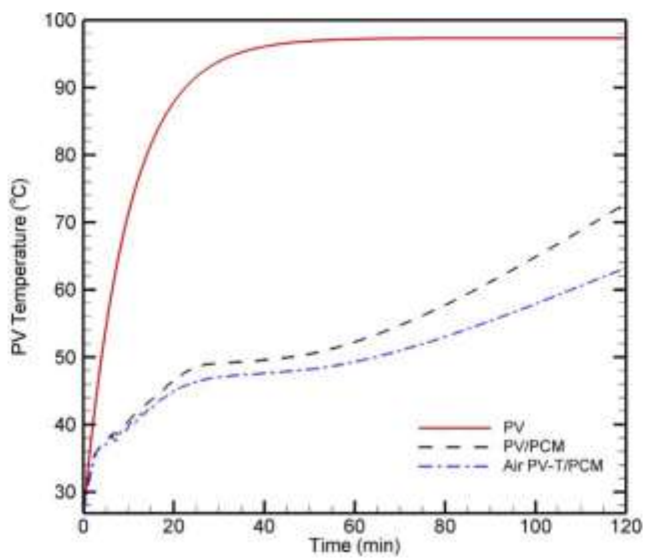

Fig. 4. Variation of PV cell temperature with time.

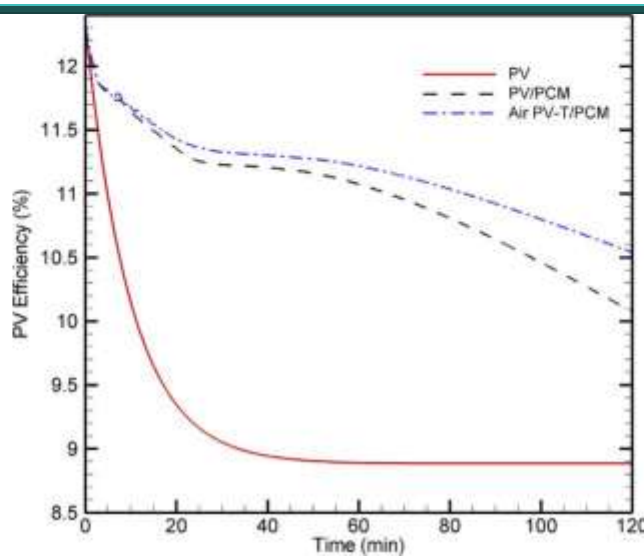

Fig. 5. Variation of PV efficiency with time.

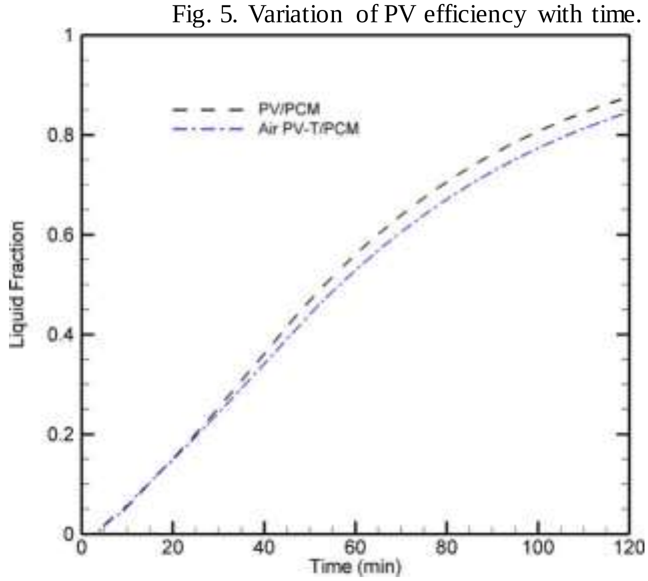

Fig. 6. Variation of liquid fraction with time.

The liquid fraction curve with time also loses the linearity trend after the end of this convective regime of melting as shown in Fig. 6. Melting in air PV-T/PCM system is slightly less as compared to PV/PCM system as air also absorbs a part of waste heat which reduces amount of heat transmitted to PCM enclosure. Melting in PV/PCM system is 87.62% while in air PV-T/PCM system is 84.57% in duration of 120 min with an incident radiation of 800 W/m^2. There is decrement of 3.48% in liquid fraction in air PV-T/PCM system as compared to PV/PCM system but the performance of PV panel has enhanced significantly in case of air PV-T/PCM system.

3.5. OUTLET AIR TEMPERATURE AND MASS FLUX.

Fig. 7 shows the variation of air out let temperature and mass flux rate with time. Temperature of PV panel in PV/PCM system is 73.97 LC, which is still very high as compare to surrounding temperature. Addition of air-flow channel on top of PV panel can pro-duce the circulation of air and remove this excess amount of heat

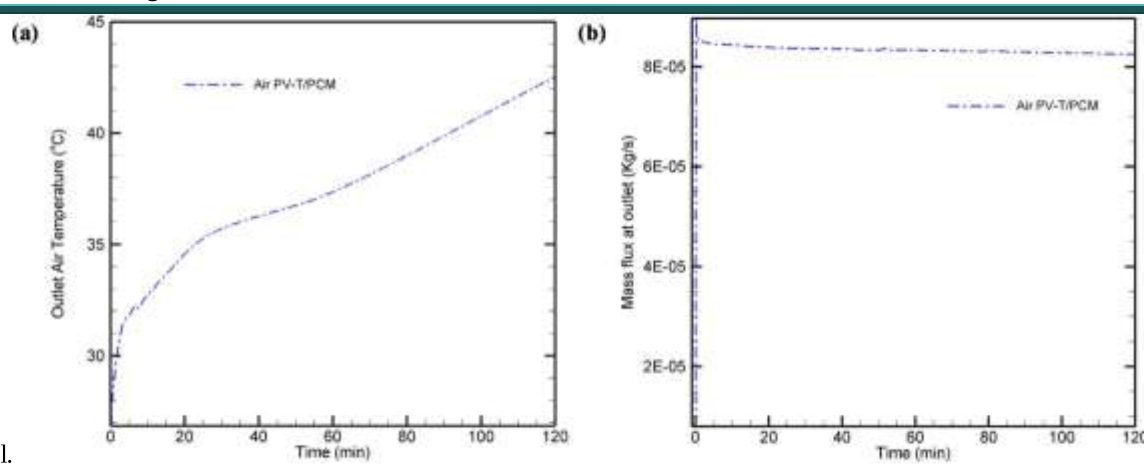

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Fig. 7. Outlet air temperature and Mass flux of air-flow channel.

due to this huge temperature difference of air and PV panel. Tem-perature of PV panel reduces to 63.24 LC after addition of air-flow channel due to natural convective heat transfer from PV panel to air. A mass flow rate of 8.25E-5 kg/s is found on the outlet of air flow channel with an outlet temperature of 42.52 LC. Attachment of air-flow channel reduces the PV cell temperature and improves its electrical performance as well as produce heated air at outlet for other purposes.

4. CONCLUSION.

In this study air PV-T/PCM system and PV/PCM system was examined to enhance the performance of PV panel with incident solar radiation. The obtained results are compared with PV panel without any attachment. It is observed that PV cell temperature reduced to 25% and 35% for PV/PCM system and air PV-T/PCM system while compared to PV system. As a result of this decrement in PV cell temperature, the electrical efficiency is augmented to 14.12% and 19.75% for PV/PCM system and air PV-T/PCM system compared to PV system. Further addition of air-flow channel and PCM enclosure also store the heat for instant and later usage. Out-let temperature of air reaches to 42.52 LC with a mass flux of 8.25 kg/s.

Substantial augmentation in overall performance of PV panel is observed as well as stored heat in form of melted PCM for later usage and heated air is available with significant outlet temperature is available for instant usage. Air PV-T/PCM system is a suit-able configuration for better performance of PV panel.

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