Modelling approach for hybrid PV/T solar panels with integrated phase change material (PCM) layer

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Abstract

This work, performed in the context of the LowUP H2020 european project, presents a modelling approach for a PV/T collector system that includes Phase Change Material in its back layer. This model will allow estimating the potential of this innovative solar system design to provide efficiency improvements within an integrated heating solution from low-valued energy sources. Here, the whole model is described focusing on the mathematical representation of the PCM layer and its associated non-linear behaviour. Main modelling assumptions are based on an energy balance for the PCM (assuming homogeneous temperature) and a simple representation of the phase change process through the parametrization of the h-T curve. Finally, the thermal resistance between absorber and PCM layer is identified as a key model parameter, and its influence is demonstrated in a preliminary simulation analysis of different designs.

Keywords: PV/T solar panels, Phase Change Materials (PCM), mathematical model, TRNSYS

1. Introduction

Hybrid PV/T solar collectors have been widely studied and developed in the past years (Chow 2010, IEA-SHC 2005). They increase global system's efficiency and enables that the amount of low-valued heat dissipated by PV cells (that will be otherwise rejected to the ambient) can be used to meet thermal energy demands (DHW or space heating) through the application of low exergy concepts in heating facilities. Indeed, this idea is being investigated within the LowUP European project (LowUP 2017), aimed at integrating different low-valued energy sources for innovative, efficient heating solutions.

LowUP works to improve the design and operating performance of this technology, particularly addressing the demonstration of a novel PV/T system that includes a Phase Change Material (PCM) in the back layer of the panels. Positive effects of the hybrid PV/T concept are expected to be enhanced. PCM will act as a thermal storage able to limit the operating cell temperature (increasing the electrical efficiency). Besides, it can be able to extend the availability of the thermal resource beyond the periods of relevant solar radiation at the end of the day.

The particular purpose of this work is to present a mathematical model for this PV/T-PCM innovative configuration. So far, some references from literature address the use of PCM to cool down PV cells and improve their efficiency (Smith et al. 2014). However, very little experience on the proposed hybrid PV/T-PCM concept has been previously reported (Browne et al. 2015) and no existing specific models are known. The proposed model will facilitate the estimation of systems' behaviour and help the design process for later implementation.

2. Description of the modelling approach

The selected modelling approach for the PV/T-PCM panel intends to account for the original PV/T geometry together with those modifications involved by the PCM layer. To this end, TRNSYS Type560 (TESS 2012) was used as the basis to account for hybrid PV/T characteristics and a self-developed PCM layer model was integrated with consistent modifications on several parameters and the original back insulation.

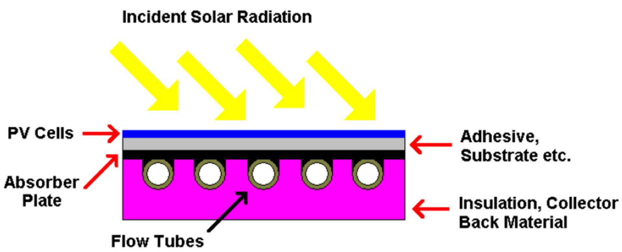
2.1 PV/T reference model

Type560 PV/T thermal model relies on algorithms from the classic work by Duffie and Beckmann (2013) and is based on the following main considerations:

- Linear relation between PV efficiency (η_{PV}), cell temperature (T_{PV}) and incident solar radiation (G_T)

  $\eta_{PV} = \eta_{nom}\chi_T\chi_G = \eta_{nom}\left(1 + eff_T\left(T_{PV} - T_{ref}\right)\right)\left(1 + eff_G\left(G_T - G_{ref}\right)\right)$(eq.1)

  where eff_T and eff_G are constant factors.
- PV cells are assumed to be operating at their maximum power condition.
- Energy balance equation for the PV cell surface neglecting conduction effects along the surface
- Classical considerations on absorbed solar radiation based on transmittance, absorptance and incident angles.
- Energy balance equation for the absorber surface, which is addressed as a classical fin problem to derive absorber plate temperature distribution
- Energy balance equation to the base area of the absorber in contact with the fluid tubes (see Figure 1)



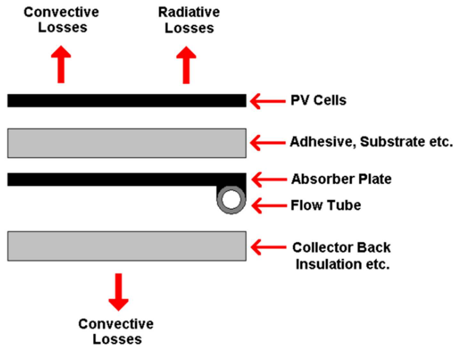


Figure 1. . (a) Schematic solar panel configuration and (b) relevant component definitions for TRNSYS Type560 PV/T model Source: (TESS 2012)

This mathematical representation allows deriving the temperature values of the different PV/T components as well as relevant output variables (both thermal and electrical). Yet, the current model does not account for the possibility of including the PCM, which requires the integration of a completely new layer with non-linear behaviour.

2.2 PCM modelling and integration

The novel PV/T-PCM system implies that the back layer (adjacent to the absorber plate) is now able to store the dissipated heat while keeping constant temperature along the phase change process. Back surface is still considered to be in contact with ambient temperature. The existence of this PCM layer involves a non-linear behaviour that cannot be modelled with a simple additional thermal resistance. Therefore, this work proposes a simple model that treats the PCM layer as a thermal storage with homogeneous temperature and is based on the energy balance equation and a simple parametrization of the enthalpy-temperature (h-T) behaviour of the Phase Change Material.

PCM temperature is affected by the heat transfer received from the collector, and simultaneously this temperature (as a boundary condition for the PV/T collector) influences the aforementioned heat transfer. Based on this, the energy balance to the PCM 'storage' layer provides its energy content at every timestep.

$$E_{i+1} = E_i + \Delta t \cdot \left(\dot{Q}_{PV/T,i} - \dot{Q}_{loss,i}\right) \qquad \text{(eq.2)}$$

Then, from the h-T curve of the material and the energy content, the PCM layer temperature is obtained. The parametrization of this h-T behaviour is described next. Figure 2 represents the h-T curves corresponding to different real heating and cooling processes of a given PCM (Belmonte et al. 2016). Although an idealized thermal behaviour with constant melting temperature is often considered when analysing Phase Change Materials, deviations associated to three main different effects can be observed:

- Variable temperature along the phase change process (temperature range)
- Different h-T curves (within the phase change range) for cooling and heating evolutions (i.e. hysteresis effects)
- Sub-cooling effects that makes the PCM requiring to achieve colder temperatures than the 'normal' melting temperature range in order to start solidification (therefore, once the freezing process starts, the

temperature increases slightly).

The present PCM model defines 3 parameters: melting temperature (T_{melt}), melting range ($range_{PCM}$) and melting hysteresis ($hyst_{PCM}$), which allows accounting for most of common h-T behaviours with reasonable accuracy (see Figure 2). Sub-cooling effects are neglected by this model.

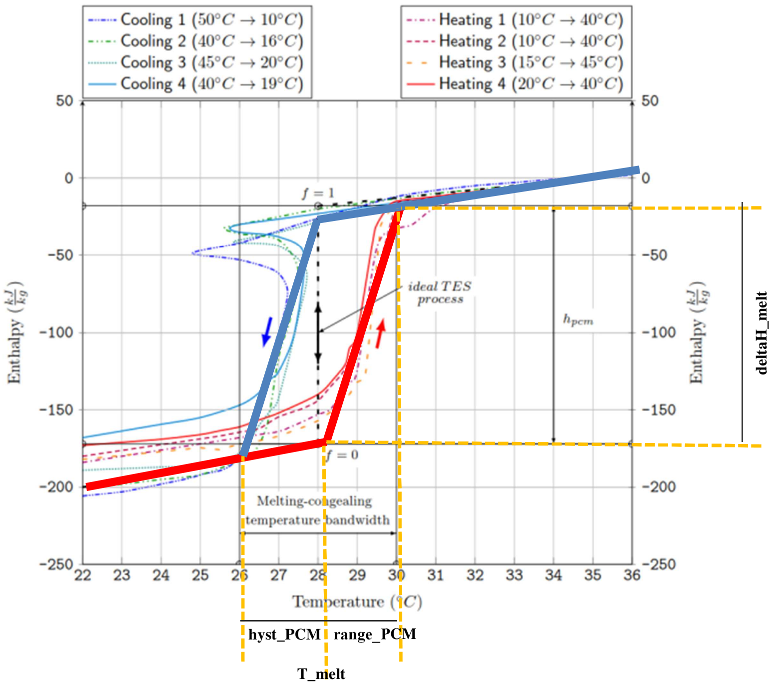


Figure 2. h-T behaviour of a particular PCM (Source: Belmonte *et* al. 2016) and definition of related model parameters

The PCM layer model was developed in C++ and integrated in the corresponding new TRNSYS type (Type261). Model inputs and outputs (required to connect the new type to other modelling components) as well as internal model parameters are collected in Table 1.

Table 1. Inputs, outputs and internal parameters for the PCM layer model

Model Inputs	
T_ini_PCM	Initial temperature of the PCM
A_coll	Area of collector surface
ePCM	Thickness of the PCM layer
Q_PVT	Heat transfer from the absorber to the PCM layer
T_ext	External (ambient) temperature
Model Outputs	
T_PCM	Temperature of the PCM layer
E_PCM	Energy level of the PCM layer
Q_loss	Heat transfer losses from the back surface of the PCM layer
f	Melted fraction of PCM (0 = completely solid; 1 = completely liquid)
Internal Parameters	
U_loss	Overall heat transfer coefficient from the PCM layer to the ambient temperature (including insulation and convective/radiant external thermal resistance)
Rho_PCM_liq	Density of the PCM liquid phase
Rho_PCM_sol	Density of the PCM solid phase
Cp_PCM_liq	Specific heat capacity of the PCM liquid phase
Cp_PCM_sol	Specific heat capacity of the PCM solid phase
T_melt	Melting temperature of the PCM
deltaH_melt	Specific enthalpy
Range_PCM	Characteristic temperature range for the phase change process (see Figure 2)
Hyst_PCM	Characteristic temperature hysteresis for the phase change process (see Figure 2)

Finally, in order to enable the integration of the proposed model, the thermal resistance of the Type560's back layer was modified and new connections between both TRNSYS components (560 for PV/T and 261 for PCM) were defined:

- PCM temperature is given to the PV/T model as the back surface environment boundary condition.
- Heat transfer through the PV/T back surface is given to the PCM model as an input.

It should be remarked that the thermal resistance between the absorber and the PCM layer is one of the key parameters of the proposed model. Theoretical derivation of this parameter is not evident, so its value should be calibrated with experimental data from manufacturer tests or real operation monitoring data.

3. Results and discussion

To explore the behaviour of the proposed modelling approach and demonstrate the influence of the above-mentioned thermal resistance some simulations were conducted for the first week of January in Seville (Spain). The TRNSYS simulation setup showed in Figure 3 was devised based on the following conditions and simulation hypotheses:

- Two solar systems with the same dimensions and configuration, except the back layer : PV/T panel with conventional back insulation, and PV/T panel with integrated PCM layer (3 cm-thick)
- PCM melting temperature of 30 ºC.
- Ideal energy demands able to return 25 ºC to the panels.
- Simple control strategy with pump operation turned on if minimum solar radiation is available or if outlet water temperature above 25 ºC can be achieved (even without solar radiation).

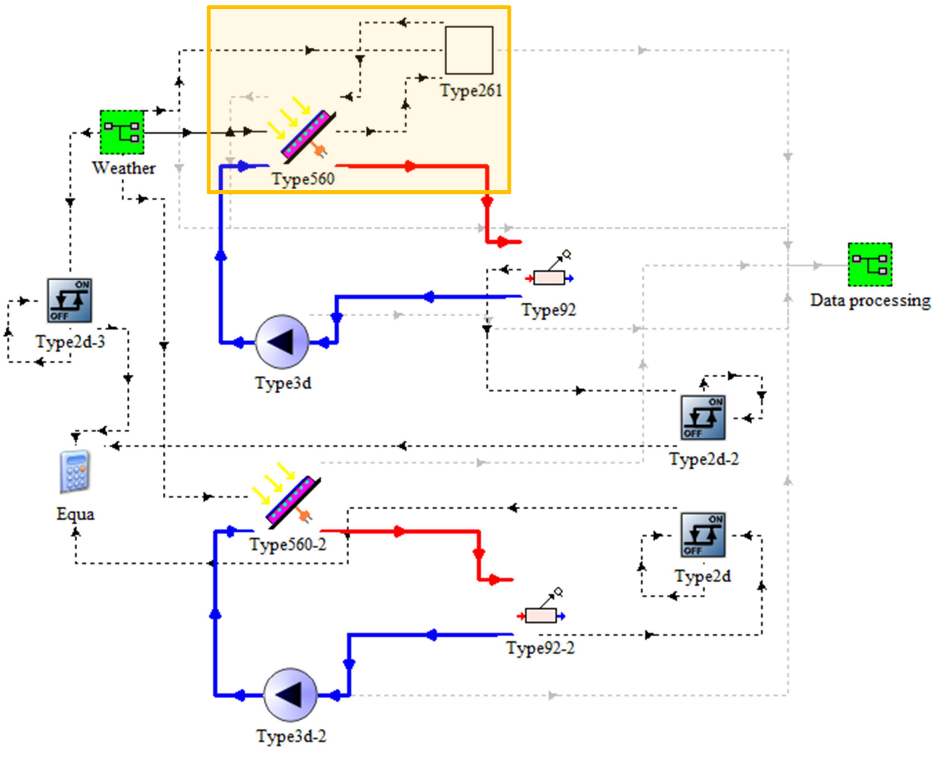
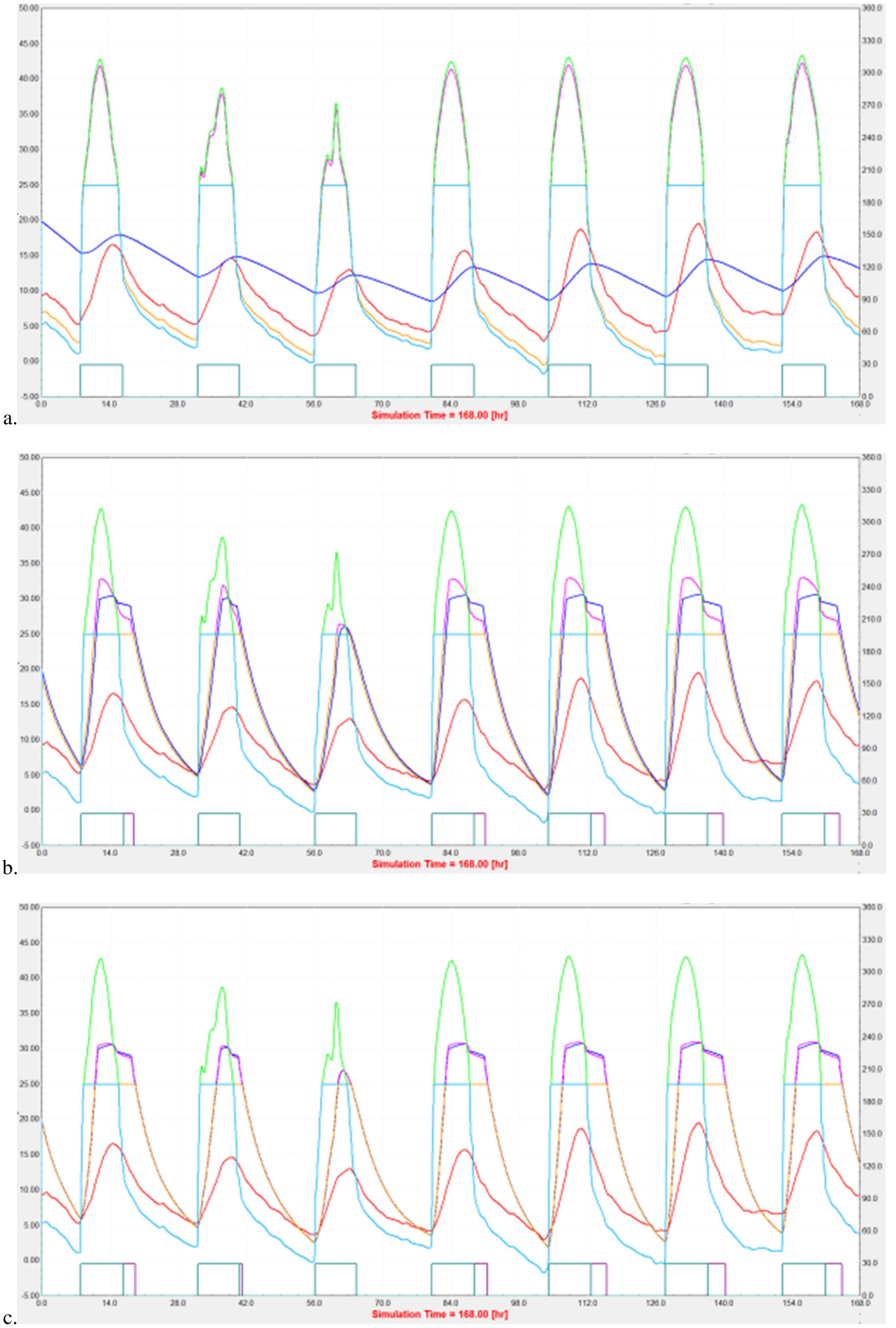


Figure 3. TRNSYS simulation setup for PV/T-PCM model analysis

A preliminary sensitivity analysis was done by modifying the thermal resistance (R) between the absorber and the PCM layer in the PV/T-PCM system: a) R = 0.07 $m^2 \cdot K \cdot W^{-1}$, b) R= 0.0007 $m^2 \cdot K \cdot W^{-1}$ and c) R= 0.00007 $m^2 \cdot K \cdot W^{-1}$. Figure 4 shows the obtained results.



Legend:
Left axis – Temperatures (ºC):
T_ext (red), T_PCM (dark blue), Tfluid,out_wPCM (pink), Tfluid,out_woPCM (green), Tfluid,in_wPCM (orange), Tfluid,in_woPCM (light blue)
Right axis – Mass flow rates (kg/h):
m_woPCM (dark green), m_wPCM (purple)

Figure 4. Temperature evolutions for PV/T system with and without PCM considering different values of the characteristic thermal resistance between the absorber and PCM layer (R in m2·K·W-1): (a) R = 0.07, (b) R= 0.0007, (c) R= 0.00007

One can observe clearly different behaviours of the PCM and fluid outlet temperatures depending on the R-values. If the R-value is high enough, the model reflects a decoupling effect between the thermal responses of the fluid and the PCM layer. In such case, the PV/T-PCM behaviour is very similar to the original PV/T system.

However, as the considered R-value is reduced, the PCM layer plays a relevant role in the overall thermal behaviour of the panel. The PCM layer absorbs enough heat from the PV/T configuration to reach its melting point. Then, less heat transfer to the fluid takes place and the outlet fluid temperature is clearly lower than that from the PV/T system.

Additionally, at the end of the day that heat stored into the PCM layer enables panel temperatures to decrease slowly and daily system operation to be extended beyond the solar radiation availability schedule. It is difficult to say how close to the first or the second option will be. Then, within the proposed model, the R-value will be a characteristic parameter of a given PV/T-PCM panel product that requires to be calibrated with experimental data.

4. Conclusions

This work presented the development of a mathematical model for innovative renewable technology consisting of a hybrid photovoltaic-thermal (PV/T) solar panel integrating a PCM-based thermal storage in its rear side. This simple approach, with a few input parameters, provides interesting potential for integration into energy simulations, enabling contributions to the design and smart operation of sustainable heating and power systems.

The key point of the proposed model is the definition of a simple representation for the h-T behavior of the PCM in the phase change temperature range. Then, a reasoned integration of the PCM behavior together with heat transfer from the PV/T system was analyzed in terms of a characteristic thermal resistance.

Moreover, a calibration procedure was envisaged focusing on the adjustment of this thermal resistance allowing to model different PV/T-PCM systems with different designs of the coupling between the absorber (heat recovery component) and the PCM layer.

Finally, it should be noted that this model is the result of tasks developed within the LowUP European project and detailed validation of the obtained results will be accomplished in the very next steps of the project based on actual monitoring data.

5. Acknowledgements

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7. Nomenclature and symbols

Table 2. List of symbols (not detailed along the text)

Magnitude	Symbol	Units
Enthalpy	h	J/kg
Temperature	T	C
Efficiency	η	Dimensionless
Efficiency modifier group	χ	Dimensionless
Efficiency modifier constant	*eff*	C^{-1}
Solar irradiation	G	W/m^2
Energy	E	J

Table 3. List of sub-indexes (not detailed along the text)

Sub-index	Meaning
i	Time instant 'i'
G	Solar radiation
loss	Back heat losses
PV	Photovoltaic panel
PV/T	Photovoltaic-thermal panel
nom	Nominal
ref	Reference
T	Cell temperature