# EXPERIMENTAL VALIDATION OF CFD MODELLING FOR THERMAL REGULATION OF PHOTOVOLTAIC PANELS USING PHASE CHANGE MATERIAL

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## ABSTRACT

Photovoltaic (PV) electrical conversion efficiency decreases with increased cell temperature. Phase change material (PCM) absorbs latent heat during phase change from solid to liquid and when integrated on the back of PV, can regulate its operating temperature. A 2D Ritz-Galerkin model was developed to simulate the temperature evolution on a reference PV and on this novel application with integrated PCM. Isoparametric spatial discretization was performed with a quadrilateral interpolation function. A four point 2D Gauss Legendre numerical integration was used to solve integral expressions of discretized forms. Temporal discretization was undertaken by finite difference and the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was used to find divergence free velocity and pressure. Boussinesq approximation was used to simulate change in density with temperature and volume and the velocity suppression technique was used to incorporate the solidification phenomenon. A moving boundary condition was applied at the PCM and density as a function of temperature was used to visualize the solid-liquid interface position. Validation experiments were performed at insolations of 500 W/m$^2$, 750 W/m$^2$and 1000 W/m$^2$ in indoor conditions. Simulated results of temperature evolution of an integrated PV/PCM system were compared with experimental results to validate the developed model.

Keywords: Photovoltaic, Phase Change Material, Ritz-Galerkin Model.

## NOMENCLATURE

| | |
|---|---|
| $\Omega$ | Domain |
| $\Gamma$ | Boundary |
| $e$ | Element |
| PV | Photovoltaic |
| PCM | Phase Change Material |

## INTRODUCTION

Crystalline silicon PV, operating above 25 ºC typically, shows a temperature-dependent power decrease between 0.4%/K to 0.65%/K (Radziemska 2003). A passive heat removal technique for thermal regulation of PV uses PCM integrated on the back of the PV(Huang et al. 2004). PCM (RT20) was selected for thermal regulation with a melting temperature of ~25 ºC and heat of fusion ~142KJ/Kg(Hasan et al.). PCM was encapsulated in the aluminium container and attached to the back of PV as shown in Fig. 1.An aluminium container was used as its high thermal conductivity enabled rapid heat transfer to PCM.

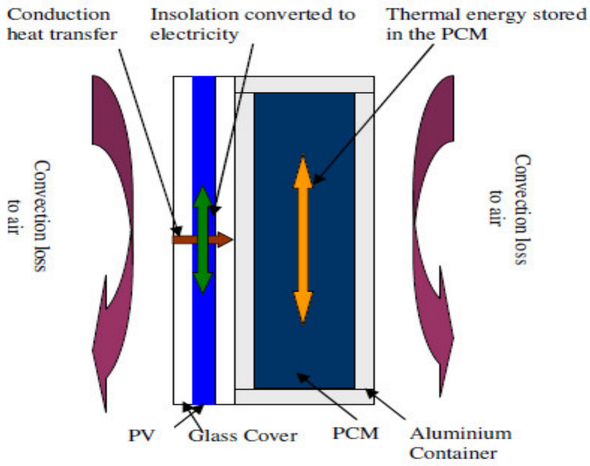


Figure 1: PV/PCM system

## MODELLED HEAT TRANSFER MECHANISM IN PV/PCM SYSTEM

Heat loss due to conduction, convection and radiation was considered in the PV/PCM system. A 2D heat diffusion equation (Mills 1999) was solved to simulate heat transfer in solid regions. The 2D convection equation (Usagi et al. 1972) was solved to simulate heat transfer due to convection. The Neumann Boundary condition was applied at the front surface of the PV panel and Dirichlet boundary condition at back surface of the PV. A continuum model of conservation of mass, momentum and energy equation (Bennon et al. 1987) was solved to simulate heat transfer in PCM. A moving boundary condition was applied to PCM to track the solid-liquid interface.

## RITZ-GALERKIN MODEL AND DISCRETIZATION

The finite element method is a powerful computational technique for the solution of differential and integral equations which is a generalization of the classical Variational (i.e. the Ritz) and weighted-residual (e.g. Galerkin) methods.(Reddy et al. 1983) This is accomplished by subdividing the given domain $\overline{\Omega} = \Omega \cup \Gamma$ into sub domains, called finite elements. The domain of an element is denoted by $\Omega^e$ and its boundary by $\Gamma^e$ and these sub domains are assembled (non-overlapping) to form approximated given domain $\Omega$ which is called the finite element mesh. The element $\Omega^e$ can be a triangle or quadrilateral, and the degree of interpolation over it can be linear, quadratic, and so on. The primary steps in the finite element analysis of a typical problem are listed below (Reddy et al. 1983; Reddy 1984; Reddy 1991; Reddy 1993; Meschke 2004);

i) Mesh generation and weak formulation of the differential equation

ii) Development of the finite element model of the problem using its weak form

iii) Assembly of finite elements to obtain global system of algebraic equations

iv) Applying boundary condition and solution of equations

v) Post processing of the solution.

The choice of interpolation function depends on complexity of geometry (e.g. curve-edged areas) and accuracy of approximation. Weak formulation of the differential equation and its finite element model development is been described in literature and it is not in the scope of this paper.

The Assembly of the elements to the system is realized by different strategies, mainly direct addition of components and an element and system specific compatibility matrix(Lewis et al.; Meschke 2004). Array index can be made for assembly whose size equals to the number of degrees of freedom per element(Kwon). Efficient System nodes numbering is important to have minimum semi-bandwidth of the resultant matrix (Griffiths et al.; Bathe 1996) Skyline technique is used to effectively store elements below the skyline of system matrix to reduce memory usage.(Bathe 1996) but during the solution by Gaussian elimination, "fill-in" results in a burden on memory and iterative schemes been sought for solution of large systems.(Griffiths et al.) Other storage methods are profile storage, frontal and sparse storage methods. Assembling of only non-zero coefficients of system matrix in one dimensional array is another possibility (Rajasankar et al. 2000; Douglas July 1995).

Weak formulations of all the differential equations were determined to obtain a Ritz-Galerkin model(Reddy 1993). Isoparametric spatial discretization was performed using a quadrilateral shape function (Meschke 2004). Geometry and all variables were approximated. Finite difference was used for temporal discretization (Reese 2003).

## EXPERIMENTAL SETUP

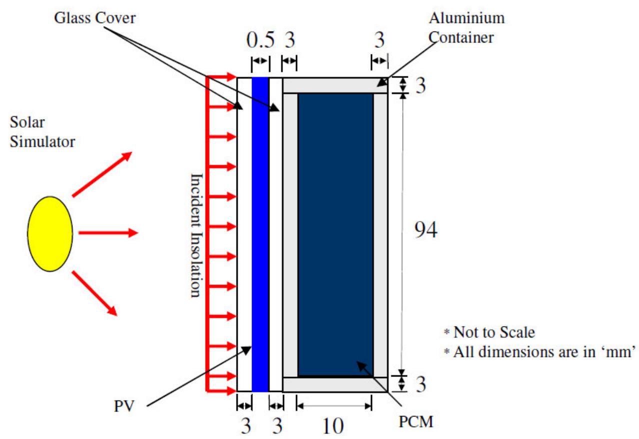


Figure 2: Schematic diagram of experimental setup and dimensions*

An aluminium container was attached to the back of the PV and filled with PCM as shown in Fig. 2. Five thermocouples were attached to the front and three thermocouples were attached to the back surface of the PV to record the temperature evolution on the PV at simulated insolations of 500W/m$^2$, 750W/m$^2$ and 1000W/m$^2$ in indoor conditions at an ambient temperature varying in the range of 20 ºC to 25 ºC.

## RESULTS AND DISCUSSIONS

Fig. 3 shows both experimental and simulated temperature evolution on front of the reference PV at insolations of 500 W/m$^2$, 750 W/m$^2$and 1000 W/m$^2$ in indoor conditions. There was fluctuation in irradiation from solar simulator which was recorded as $\pm 10\,\mathrm{W/m^2}$ and error in thermocouples readings were $< \pm 1\%$ . Variations of ambient temperature during experiments and in simulated results are shown in Fig. 4. Simulated results show good agreement with experimental results and with variation due to ambient temperature. At 1000 W/m$^2$, initial ambient temperature was 20ºC and it rises to 23ºC and simulated ambient temperature was 23ºC so initial gradient of temperature evolution during experiment is higher than simulated results but as ambient temperature coincide, the gradient of both curves were in good agreement. The maximum temperature at 1000 W/m$^2$ was ~57 ºC in 30 minutes while in the same duration, temperature rise was ~50 ºC and ~ 43ºC respectively for insolation levels of 750W/m$^2$ and 500 W/m$^2$.

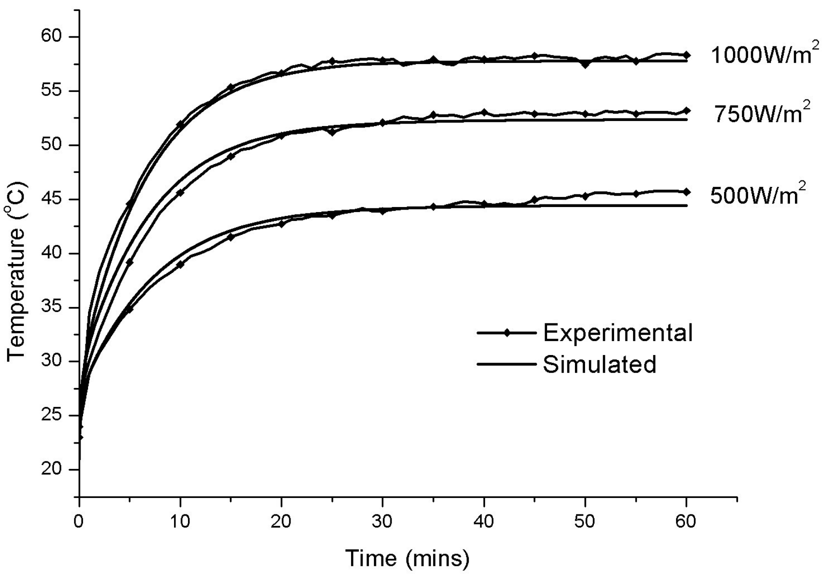


Figure 3: Temperature evolution at PV front surface (without PCM)

The simulated ambient temperature for insolation levels of 750W/m$^2$ and 500 W/m$^2$ was 25ºC. However, during the experiment, the ambient temperature was continuously rising. Therefore, the actual experimental temperature gradient was higher at the end, compared to the corresponding simulated gradient. This shows ambient temperature variation has to be considered for accurate simulation.

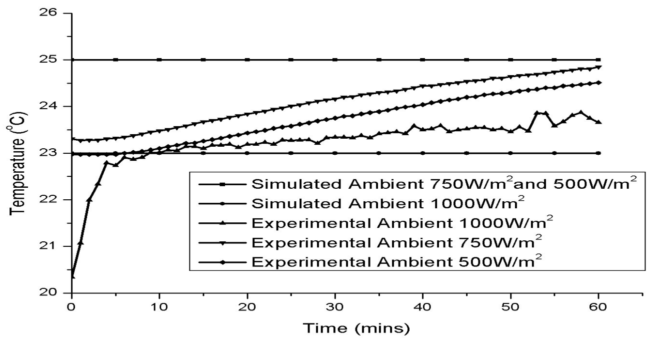


Figure 4: Measured experimental ambient temperature variation during experiment and simulated temperature (without PCM)

Fig. 5 shows the experimental and simulated temperature evolution on front of the PV panel integrated with PCM (RT20) at insolations of 1000W/m$^2$, 750W/m$^2$ and 500W/m$^2$. The variation in melting completion for experimental and simulated result is due to Dirac delta function which were used for simulating energy storage at given temperature range of 25$^o$C to 34 $^o$C and had an accuracy of $\pm 0.5^o C$. Nevertheless, the trend of temperature evolution was consistent with experimental result and validates the CFD model.

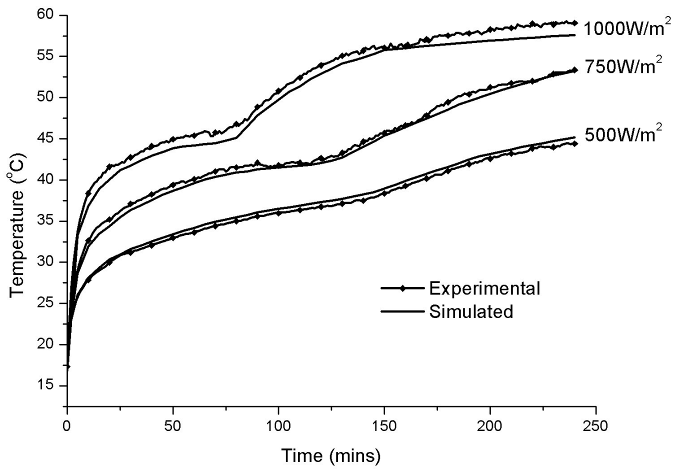


Figure 5: Temperature evolution at PV front surface with PCM (RT20)

## CONCLUSION

We have shown that 2-D Ritz-Galerkin model is a very useful tool for simulating PCMs. RT20 can regulate temperature of PV, thereby increasing the electrical output of it. Ambient temperature variation has to be considered for accurate simulation of temperature evolution at PV.

## ACKNOWLEDGEMENT

The authors would like to acknowledge the Higher Education Authority through Strand 3 funding, Science Foundation Ireland through their Research Frontiers Program and the Research Support Unit at Dublin Institute of Technology. I would also like to acknowledge COST Action TU0802: "Next generation cost effective phase change materials for increased energy efficiency in renewable energy systems in buildings" for providing an invaluable platform to discuss and develop this work.

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