EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THERMAL PERFORMANCE OF A CROSSED COMPOUND PARABOLIC CONCENTRATOR WITH PV CELL

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ABSTRACT

Crossed compound parabolic concentrator (CCPC) is a solar energy device used to increase the photovoltaic (PV) cell electrical power output. CCPC's thermal and optical performance issues are equally important for a PV cell or module to work under a favourable operating condition. However, most work to-date is emphasised on its optical performance paying a little attention to the thermal characteristics. In this contribution, we investigate the thermal performance of a CCPC with PV cell at four different beam incidences (0°, 10°, 20°, 30° and 40°). Initially, experiment is performed in the indoor PV laboratory at the University of Exeter with 1kW/m^2 radiation intensity. 3D simulations are carried out to first validate the predicted data and then to characterise the overall performance. Results show that the temperature in the PV silicon layer is the highest at 0° and 30°, with the top glass cover of CCPC having the lowest temperature at all the incidences. The temperature and optical efficiency profiles at the various incidences predicted by simulation show very good agreement with the measurements, especially at 0° incidence. This study provides useful information for understanding the coupled optical-thermal performance of the CCPC with PV cell working at various conditions.

INTRODUCTION

CPCs are an optical device for solar energy collection. The design, optical and thermal property analysis of CPC can be traced back to 1970s [1, 2]. In that time, CPC was a trough. Currently, CPCs can be in three-dimensional shape, namely a polygonal aperture, and it is shown that the square CPC, i.e. crossed parabolic concentrator (CCPC) has a good optical performance with lower cost [3]. Thus this sort of CPCs can potentially find extensive applications in solar energy harvesting systems in future. A comprehensive review on the principles and applications of CPCs is given in [4-6].

Optical and heat transfer simulation of CPC is quite important to understand its performance [7]. In our project, we designed a hybrid roof-top PV module with CCPCs, as shown in Fig. 1(a) and a single CCPC with PV cell was isolated from the 9×9 CCPC package, and multiphysics (optical, thermal and fluid flow) simulations of a CCPC with PV cell were performed in [8] by means of ANSYS CFX 15.0 at various solar beam incidences and 1kW/m^2 radiation intensity. Good agreement in the optical performance between the prediction and observation was found and the PV cell was subject to the highest temperature when the incidence was less than or equal to 20°. However, the temperature profiles in the PV cell and on the top and back glass covers were not validated. And, the CCPC casing was not taken into account in the simulations.

In this article, we carry out thermal experiment on the same CCPC as in [8] but with an aluminate casing firstly, and then conduct optical and thermal simulations in CFX and Fluent to validate and compare different physical models and methods, respectively.

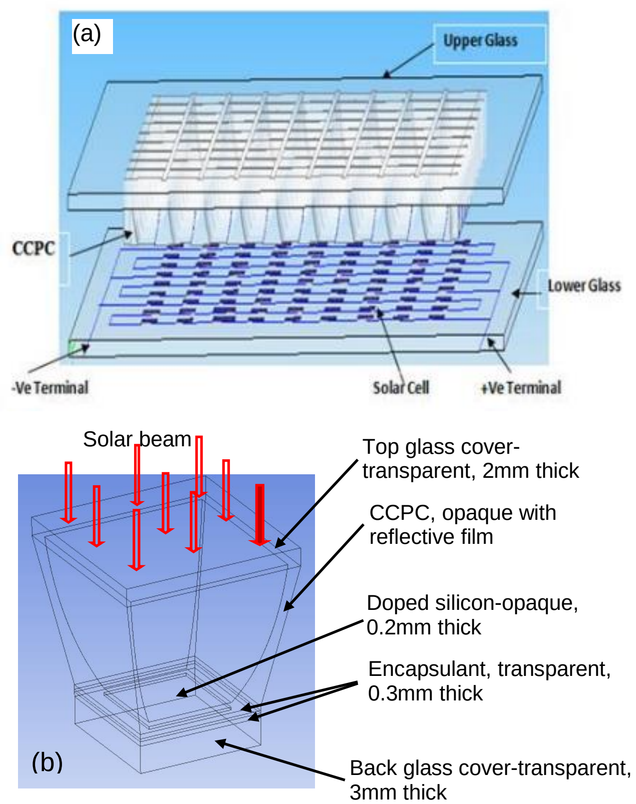

Figure 1 A PV module with CCPCs (a) and a single CCPC model with casing for thermal experiment and simulation (b)

EXPERIMENTAL STUDY

An air-filled CCPC with a solar cell and an aluminium casing was designed in [9] as shown in Fig. 1. We conducted a series of heat transfer experiments on this CCPC with solar cell in the indoor PV laboratory of the Environment and Sustainability Institute, at the University Exeter, UK.

Four thermal sensors were fixed in the top glass cover centre and edge, back cover centre and the silicon layer of the cell, respectively. Four channels of Model 27000 Multimeter/Data Acquisition System produced by Keithley Co. Ltd were activated via XLINX software to connect those sensors, thus allowed the temperature data to be collected. The CCPC model without electrical connections was illuminated under a Solar Simulator (WXS-210S-20, AM1.5G, made by Wacom Electric Co. Ltd, Japan).

A heat transfer experiment needs to last for 45min-60min to get a steady-state response. In this period, the indoor ambient temperature rises to 29^{o}C from 28^{o}C. The simulator illumining beam is unmovable and remains downwards all the time and the top glass cove is faced against the beam.

The CCPC model is fixed onto a small plastic table. The squared through hole on the table surface accommodates and holds the CCPC model, allowing free convection condition over its outside surfaces. The orientation of the CCPC model is adjusted by tilting the table two legs in one side with certain thick wood sheets to achieve desirable incidences, such as 0^{o}, 10^{o}, 20^{o}, 30^{o} and 40^{o} respectively.

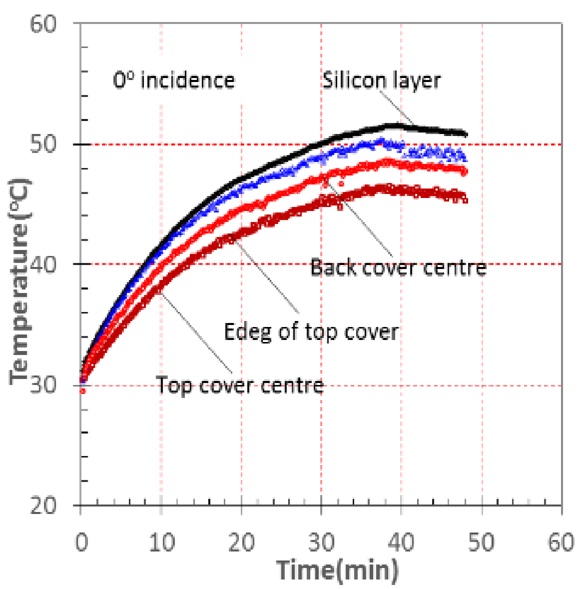

Figure 2 Temperature variations on the top and back glass covers, at the edge of top cover and in the silicon layer at 0^{o} incidence

The temperature time-history curves are illustrated in Figure 2. It is clear that the temperature in the silicon layer is the highest if the incidence is in 0^{o} and 30^{o}, confirming an existence of the highest temperature core in the layer at a small incidence. The top glass cover centre is subject to the lowest temperature at all incidences. Because the temperature at the edge of the top cover is just 2^{o}C-3^{o}C higher than the temperature in the centre, obviously there is no highest temperature spot.

COUPLED MULTIPHYSICS SIMULATION

The optical and thermal performance of the isolated CCPC with PV cell in Fig.1 is investigated numerically by a multiphysics method in ANSYS CFX 15.0. The grey optical model is involved in the simulations. The Maxwell equations are solved by making use of the Monte Carlo method on the basis of homogenous and non-scattering reflection assumption.

Solar beam is reflected and refracted when travelling through an interface between the two media. It is assumed that the solar radiation is unpolarised with two components under an equal intensity. The angle of refraction is determined by using the Snell's law of refraction.

The air flow in the CCPC cavity is laminar and steady-state since the Reynolds number of the filled air flow is less than 100. In a stationary reference frame, the instantaneous continuity, momentum and thermal energy equations are solved [10]. The Boussinesq model is adopted to calculate the density difference in the momentum equations.

In the solid domains, the conduction heat transfer equation is held. The governing equations for the fluid flow and heat transfer, including the sunlight radiation, are solved together under a set of proper boundary conditions until a desired convergence is reached.

The optical, thermal and radiative properties of the medium used in the models are listed in [8]. Four kinds of boundary condition are composed. The first is the interface between the solid domain and fluid or other solid domain; the second is the boundary that is subject to natural convection with a certain heat transfer coefficient; the third is the boundary that can emit radiation; and the fourth is the boundary that can receive the sunlight radiation.

On the top glass cover, the upper surface is subject to a 1kW/m^2 uniform radiation intensity whose incidence angle is respectively set to be 0˚, 10˚, 20˚, 30˚ and 40˚ in the west-east plane. In the simulation, this intensity is set to be a boundary source to drive the whole heat transfer process within the CCPC with a solar cell. For comparison with the experimental observations, the ambient temperature was given to be 28.5^{o}C to represent the slightly variable ambient temperature between 28^{o}C and 29^{o}C in the experiments.

The average temperatures on the top glass cover, silicon layer and back glass cover are compared with the experimental measurements in Fig. 3(a). The agreement of temperature between the prediction and measurement on the top cover is excellent, the temperature in the silicon layer and back glass cover is 2^{o}C-3^{o}C below the measurements at 0^{o} incidence. Overall good agreement for temperature has received with this CCPC model.

The temperature contour on the surfaces of top cover, CCPC casing, encapsulant, silicon layer and back cover is illustrated in Fig. 3(b). Even though there is a highest temperature spot on the top cover, the temperature difference on the top cover is just 6^{o}C.

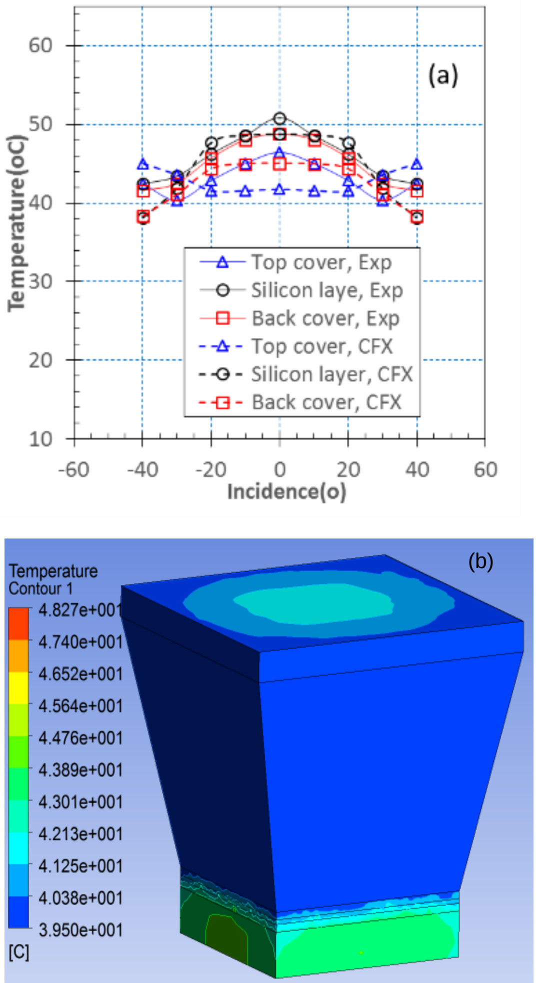

Figure 3 Comparison of average temperature between prediction and measurement based on the new model as well as temperature contour on outside surfaces of the model, (a) average temperature versus incidence, (b) temperature on outside surfaces at 0° incidence

PURE THERMAL SIMULATION

Currently, there is another numerical method to treat the heat transfer in CCPC with PV cell. In this method, a ray trajectory analysis in a CCPC is done firstly to get its optical efficiency, then the available radiation energy onto the PV cell surface is estimated by the efficiency and total radiation energy at the entrance to the CCPC. Subsequently, an energy flux is calculated by dividing this available energy with the CCPC aperture. Finally, the energy flux is added on the PV cell surface as a heat source flux to drive a heat transfer process in the CCPC. The details of this procedure are in [11, 12, 13].

To examine if this approach is applicable in the present case, a series of heat transfer simulations under various incidences are conducted. The CCPC and cell geometrical models are the same as shown in Fig.1. Under the 1kW/m^2 radiation intensity, the decided heat fluxes upon the cell surfaces are 3076.53, 2972.04, 2856.54, 1318.05 and 644.28W/m^2 with respect to 0°, 10°, 20°, 30° and 40° incidences respectively, by using the optical efficiency curve predicted with CFX shown in Fig. 5. Then a steady heat transfer simulation is launched in CFX based on the computational models above by applying that heat flux onto the cell surface as heat source flux. In the simulation, the radiation model and corresponding boundary conditions are removed from the fluid and solid domains, but the rest of the physical models and boundary conditions remain unchanged.

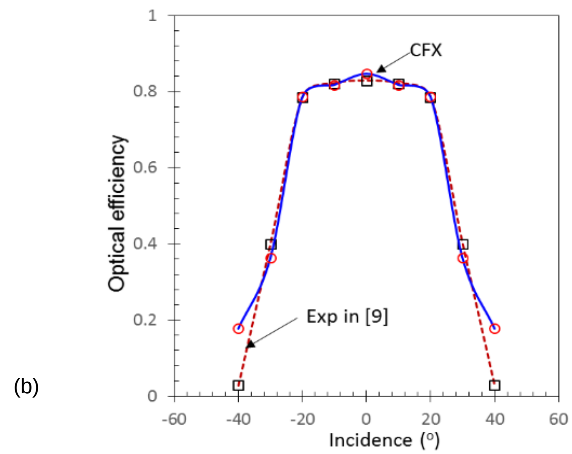

Figure 5 Experimental and predicted optical efficiencies

Fig. 6 illustrates the temperature contours over the top, back glass covers, CCPC casing, cell outside surfaces at 40° incidence as well as average temperature on the two covers and the cell in terms of incidence. It is seen that the cell is the hottest element; apparently this is in agreement with the experimental observations in Fig. 2. However, the temperature magnitude is 10°C below the observation. Note that the temperature profile in the CCPC is symmetrical as shown see Fig. 6(b).

The predicted average temperature on the back cover agrees quite well with the measurement when the incidence is equal to or less than 20°, however, this is not true for the predicted average temperatures on the top cover and cell, in which a 10°C difference temperature can be resulted against the corresponding experimental data. Therefore, the method without radiation coupled should be used with caution.

This suggests that the heat conduction in the CCPC wall plays a significant role in determining temperature profile of a CCPC with PV components.

CONCLUSION

The heat transfer experiments on a CCPC with PV cell are conducted in indoor laboratory to validate the computational modes, methods and results. The effects of the CCPC casing on heat transfer are investigated by using a CCPC model with certain thickness wall. It is confirmed the numerical method and multiphysics models utilised are effective for identifying the optical and thermal performance of the CCPC in CFX. The CCPC casing plays a very important role in heat transfer of CCPC with PV cell, and its wall thickness should be taken into account in the thermal performance simulations. Uncoupled multiphysics simulation is subject to a poor accuracy compared with the coupled multiphysics simulation for a CCPC with PV cell.

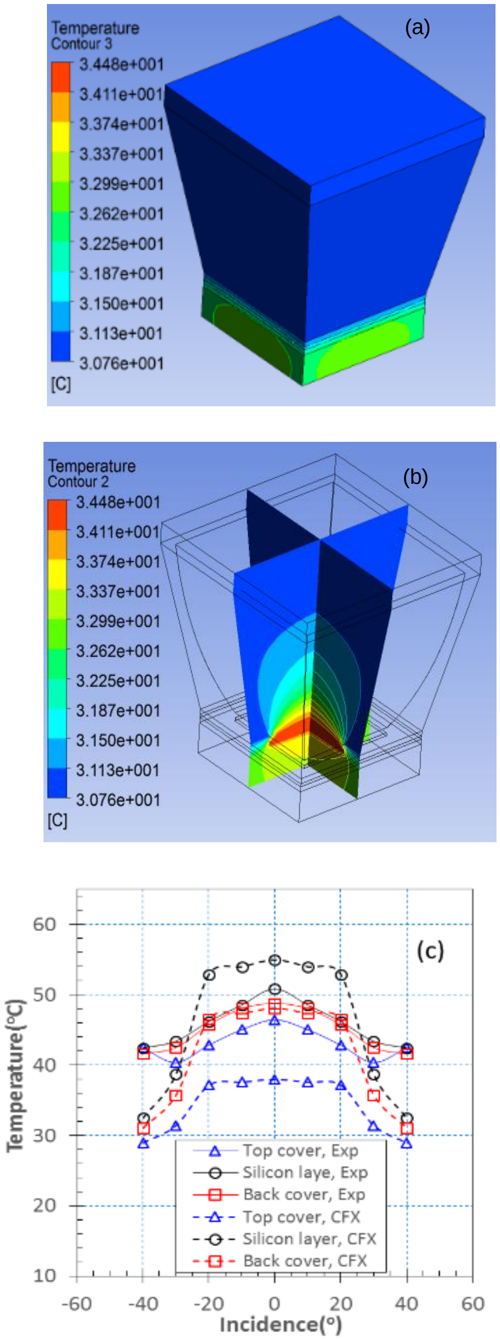

Figure 6 Temperature contours on top, back glass covers, CCPC wall and in two cross-sections as well as average temperature on top cover, cell and back cover, (a) contours on outside surfaces at 0° incidence, (b) contours in two sections at 40° incidence, (c) average temperature

ACKNOWLEDGEMENT

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