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Coupled Simulation of Performance of a Crossed Compound Parabolic Concentrator with Solar Cell

Wenguang Li[a,*], Manosh C Paul[a,*], Nazmi Sellami[b], Xian-long Meng[b], Tapas K Mallick[b], Eduardo Fernandez Fernandez[b], Andrew R. Knox[a], Andrea Montecucco[a], Jonathan Siviter[a], Paul Mullen[a], Ali Ashraf[a], Antonio Samarelli[a], Lourdes Ferre Llin[a], Douglas J. Paul[a], Duncan H Gregory[c], Min Gao[d], Tracy Sweet[d], Feridoon Azough[e], Robert Lowndes[e], and Robert Freer[e]

[a]*School of Engineering, University of Glasgow, Glasgow, G12 8QQ, UK*
[b]*Environment and Sustainability Institute, Exeter University, Penryn Campus, TR10 9FE, UK*
[c]*School of Chemistry, University of Glasgow, Glasgow, G12 8QQ, UK*
[d]*School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK*
[e]*School of Materials, University of Manchester, Manchester, M13 9PL, UK*

Abstract

An optimal installation of a compound parabolic concentrator (CCPC) into a scalable solar thermoelectrics and photovoltaics system is desirable by applying analytical tools to improve the optical and thermal performance of a CCPC with a solar cell. In this paper, the optical and thermal performances of an isolated CCPC with solar cell are investigated by employing commercial software 'ANSYS CFX 15.0' with a coupled optical grey and multiphysics model. Numerical results are validated against the experimental data at various incidence angles, especially for the optical concentration ratio and optical efficiency. Results confirm that 'ANSYS CFX' is an effective numerical tool for determining correctly both the optical and thermal behaviour of CCPC. The very important finding is a highest temperature core in the silicon layer of solar cell which may be responsible for a solar cell to work properly. The limitation of the work is that the electric performance of the solar cell is not involved and the simulations are steady.

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Keywords: crossed compound parabolic concentrator; solar cell; thermal performance; sunlight radiation; heat transfer; heat flux

1. Introduction

A Compound Parabolic Concentrator (CPC) describes an optical devices applied for solar energy collection. Over the years, CPCs have experienced an extensive development because they can achieve very high levels of concentration to maximise solar insolation and thus improve solar cell efficiency. The design of both optical and thermal property analysis of a CPC can be traced back to 1970s [1, 2]. In that time, CPC is a two-dimensional shape, i.e. a trough. Usually, a CPC cavity is very deep and it transpires

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that a large portion of the top of the 2D design can be removed without loss of optical performance [2, 3]. Therefore, CPCs are always truncated in engineering. Currently, CPCs can be in three-dimensional shape, namely a polygonal aperture, and it is shown that the square CPC has a good optical performance and lower cost [4]. Thus, this sort of CPC can potentially find significant applications in solar energy harvesting systems.

In order to augment solar energy utilisation efficiency, an integrated or hybrid CPC, photovoltaic (PV) and thermal technique is put forward in [5-10]. In our SUNTRAP EPSRC project, it is intended that an integrated CPC, PV, TEG (thermoelectric generator) and thermal technique can achieve an increased utilisation efficiency. Nevertheless, it is necessary to establish a numerical method for characterizing optical and thermal performance and optimizing design of CPC with solar cells.

In the paper, we are going to tackle the optical and thermal performance of an air-filled CPC with solar cell by making use of 'ANSYS CFX 15.0' based on a coupling between sunlight radiation and conductive heat transfer in fluid and solid domains.

2 Models and Numerical Methods

2.1 Geometry of CPC and Solar Cell

An air-filled CPC or CCPC (crossed CPC) was designed and its optical performance was characterized by using a 2D ray trace from in-house code [11]. Subsequently, this CCPC was incorporated into a 9×9 array to manufacture a PV module. Except the CCPC, the PV module consists of a top glass cover, a solar cell (two-layer sylgard elastomer and a doped silicon layer in between) and a back glass cover. The module was illuminated by a sun simulator in a 25 $^{\circ}$C dark room of an indoor laboratory with 1000 W/m^2 uniform radiation intensity under various incidence angles [12]. For the PV module, the electrical performance and temperature on the back glass cover were measured and sampled. We isolate one CCPC from the module and use this as a physical model for the optical and thermal analysis, as shown in Fig.1. The detailed profile of the CCPC is given in [11], while the thickness of the solar cell layer is given in [13].

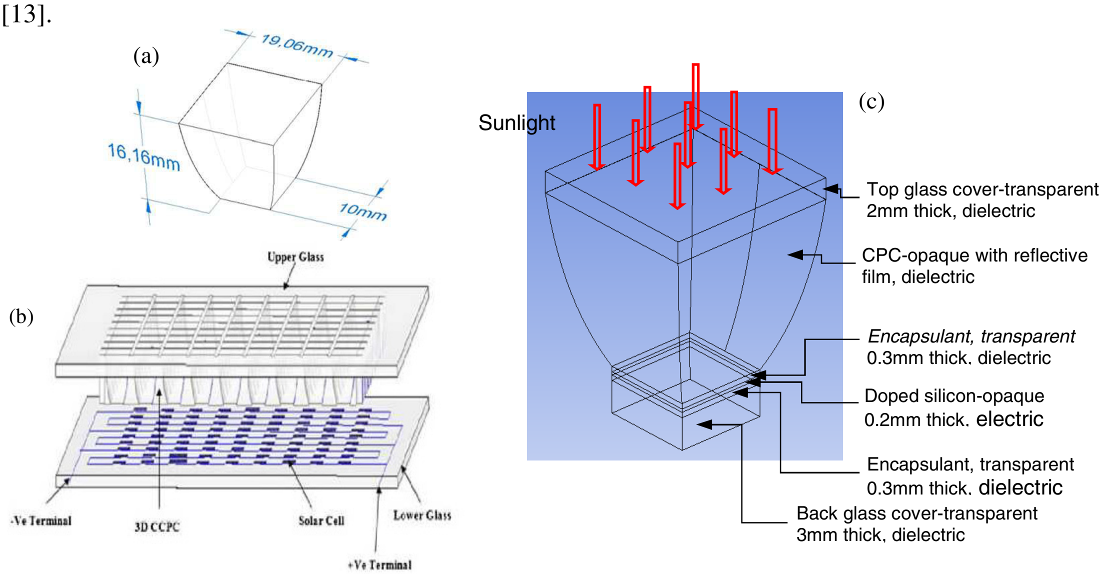

Fig. 1 Physical model of CCPC with solar cell: (a) geometry of CCPC [11], (b) 9×9 array of CCPC with PV module used in experiment [12], (c) an isolated CCPC with solar cell from the module.

Sunlight is an electromagnetic wave with a spectrum that can travel in any medium and be described by the Maxwell equations. A CCPC with solar cell can absorb, emit and scatter sunlight during its propagation. For a plane-parallel medium, the Maxwell equations can be converted into monochromatic radiation intensity as presented in [14].

In this study, we solve the Maxwell equations with an assumption that the medium is grey, homogenous and there is no scattering reflection such that the radiative properties of the medium are independent to the wavelength of sunlight.

Sunlight is reflected and refracted when travelling through an interface between two media. In ANSYS CFX modelling, this is considered by assuming radiation which is unpolarized and two-component subject to an equal intensity. The angle of refraction is determined by using the Snell's law of refraction.

Reynolds number of the filled air flow in the CCPC is less than 100, suggesting the flow behaviour is laminar. Additionally, the air flow is considered to be steady-state. In a stationary reference frame, the instantaneous continuity, momentum and thermal energy equations are illustrated in [14]. Further, the Boussinesq model is adopted to calculate the density difference in the momentum equations.

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

2.3 Medium Properties, Boundary Conditions and Numerical Methods

The optical, thermal and radiative properties of the medium used in the models are listed in Table 1. Four kinds of boundary condition are available in the CCPC optical and thermal performance prediction. The first is the interface between the solid domain and fluid or other solid domain; the second is the boundaries such as the four side surfaces of three layers, CCPC film, the top, bottom outside surfaces of up and back glass covers that are subject to a heat transfer coefficient of 10W/m^{2}K; the third is the boundaries that can emit radiation; the fourth is the boundary that can receive the sunlight radiation.

Table 1 Thermal and radiative properties of glass, air, sylgard, silicon and reflective film at 25 °C

Medium	Glass	Air	Sylgard	Silicon	Reflective film
Density, ρ (kg/m^3)	2500	1.185	1030	2330	N/A
Specific capacity, c_p (J/(kgK))	750	1004	1100	712	N/A
Thermal conductivity, k (W/(mK))	1.4	0.0261	0.16	148	N/A
Absorption coefficient , α (m^{-1})	2	0.01	2	70000	N/A
Scattering coefficient, γ	0	0	0	0	N/A
Refractive index, n	1.4	1.0	1.42	4	N/A
Emissivity, ε	0.94	0	0.9	0.672	0.06
Diffuse fraction	0	0	0	0	0

On the top glass cover, the upper surface is subject to a 1000 W/m^2 uniform radiation intensity whose incidence angle is respectively set at 0°, ±10°, ±20°, ±30° and ±40° in the west-east plane. In ANSYS CFX, this intensity is set to be a boundary source to drive the whole heat transfer process within the CPC with a solar cell.

The fluid and solid domains are divided into 105,660 nodes and 82,309 hexahedral elements, respectively. The laminar air flow and thermal analysis in the CCPC are solved based on the finite volume method. A high resolution scheme is used to discretise the advection terms in the continuity, momentum and thermal energy equations. The maximum number of iterations is 8000, and the root mean square residual tolerance is 1×10^{-6}.

The Monte Carlo method is applied to solve the sunlight propagation in the participating media: air, glass, sylgard, silicon with 200,000 number of histories under the 64-target coarsening rate and 20,000 number of small coarse grid size. During the solution process, the thermal and radiation energy equations are coupled when the fluid flow governing equations are solved for each 30 iterations.

3 Results

3.1 Optical Concentration Ratio and Efficiency

A series of simulations are conducted for each different incidence angles to investigate the effects of the sunlight incidence on the optical and thermal performance of the CCPC. The optical concentration ratio and optical efficiency predicted with ANSYS CFX is illustrated in Fig. 2. The concentration ratio is calculated by the extracted wall irradiation fluxes on both the bottom surface of the top sylgard layer and the upper surface of the top glass cover. The optical efficiency is equal to the concentration ratio multiplying the CCPC aperture inlet-to-outlet area ratio. The optical efficiency comparison between the experimental and estimated optical efficiency η_{opt} is demonstrated in Fig. 2(a). The ray trace method described in [11, 12] leads to a substantially over-estimated optical efficiency because the radiation and heat transfer coupled effects are not taken into account in this case. However, the efficiency determined by the CFX method, where the optical, radiation and heat transfer effects are coupled, shows having a very good agreement with the experimental data. The optical and electrical experiment is done on a 9×9 CCPC module as shown Fig. 1(b) in [12]; a similar experiment is made on a 3×3 CCPC module in [11]. Note that the same CCPC geometry is kept in both experiments.

In the figure, the designed and measured optical concentration ratios under the 0° incidence are provided from [11]. The design concentration ratio is calculated by means of the well-known formula, $C_{opt} = 1-1/\sin\theta$, for which θ is the acceptance half-angle of the CCPC, $\theta = 20^{\circ}$. Obviously, under the 0° incidence, the two concentration ratios are consistent with each other.

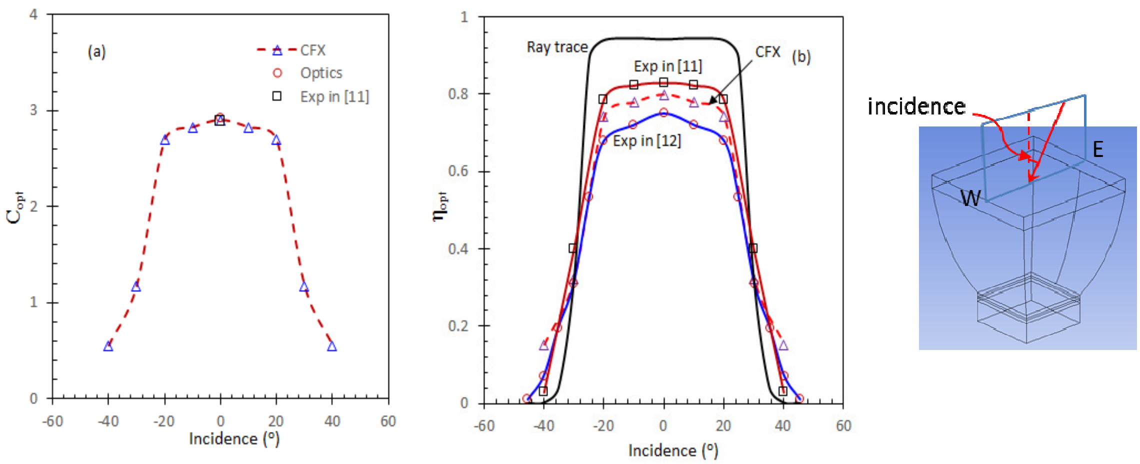

Fig. 2: Optical efficiency and concentration ratio in terms of the incidence and optical efficiency by the ray trace method [11, 12]: (a) optical concentration ratio, (b) optical efficiency.

The above comparison between the predicted and measured optical efficiency and concentration ratio suggests that the coupled CFX simulations are essential and the numerical models implemented are realistic for analysing the multiphysics effect in a CCPC with a solar cell.

3.2 Temperature Profile and Flow Pattern

Temperature contours on both the CCPC and solar cell along with the velocity vectors of the air flow within the cavity/chamber under the various incidences are presented in Fig. 3. Clearly, at small incidences, the highest possible temperature core exists in the silicon layer. However, with an increase in the incidence the core is cooled down and eventually disappears. According to Fig. 3, the optical efficiency starts to decline from 20°, suggesting the highest temperature core in the silicon layer is essential for a solar cell to work properly. If that condition is not achieved, the solar cell performance declines. Thus, the temperature drop in the silicon layer due to the less incident radiation, is responsible for the optical efficiency at a large incidence.

Moreover, less incident radiation is shed into the CCPC with an increasing incidence affecting the air velocity within the CCPC. As a result, the Reynolds number of the flow, which is based on the maximum velocity, density and dynamic viscosity of the air at 25 °C and 19.06 mm width of inlet aperture of CCPC, decreases to 15.4 from 40.7.

Under the 0° incidence, a vortex-loop is generated in the chamber and the highest velocity zone remains in the central of the chamber. With increasing incidence, the vortex-loop still exists but is twisted and squeezed; and the position of the highest velocity zone is altered and moved to the side wall gradually. Such a 3D flow pattern has not been visualized before in a CCPC system.

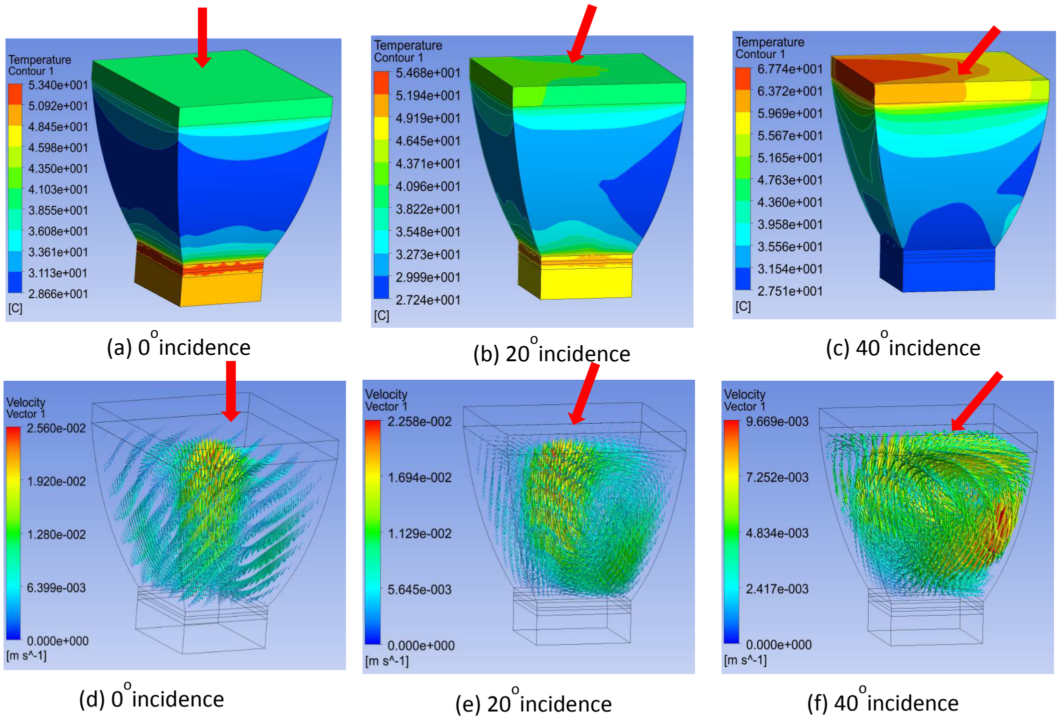

Fig.3: Temperature profile on CCPC and velocity vectors of the filled air in CCPC chamber under various incidences, (a)-(c) temperature, (d)-(f) velocity.

4 Conclusions

The optical and thermal performance of an isolated CCPC with a solar cell is examined numerically by a multiphysics method. The grey model is applied in ANSYS CFX. The optical, thermal models and numerical methods are validated against the experimental data under various incidences by means of the optical efficiency and concentration ratio. The flow patterns of the filled air in the CCPC chamber are characterised. It is confirmed ANSYS CFX is an effective tool for studying the optical and thermal performance of a CCPC and can be applied in a CCPC design to characterize its optical and thermal performance. The optical and thermal parameters of the CCPC are estimated correctly and there is a vortex-loop in the filled chamber which is affected by the incidence of sunlight. An important finding is a highest temperature core in the silicon layer which may be essential for a solar cell to work properly compared with the existing previous studies.

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Biography

Wenguang Li is a Research Assistant at the School of Engineering of the University of Glasgow. He has over 10-year experience in fluid dynamics, He received his PhD from the University of Sheffield, Great Britain, in 2007.