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## Temperature optimization of high concentrated active cooled solar cells



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### KEYWORDS

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**Abstract** Active cooling is essential for solar cells operating under high optical concentration ratios. A system comprises four solar cells that are in thermal contact on top of a copper tube is proposed. Water is flowing inside the tube in order to reduce solar cells temperature for increasing their performance. Computational Fluid Dynamics (CFD) simulation of such system has been performed in order to investigate the effect of water flow rate, tube internal diameter, and convective heat transfer coefficient on the temperature of the solar cells. It is found that increasing convective heat transfer coefficient has a significant effect on reducing solar cells temperatures operating at low flow rates and high optical concentration ratios. Also, a further increase of water flow rate has no effect on reducing cells temperatures.

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### 1. Introduction

Solar energy is going to be a main substitute for fossil fuels in the coming years for its clean and renewable nature. As the country population progresses, the energy consumption increases (Royne et al., 2005). Incident solar radiation elevates the temperature of PV cells, resulting in a drop of their electrical efficiency (Tripanagnostopoulos, 2007). The integration of photovoltaic and solar thermal technology increases the energy output per unit collector area (Omer, 2008; Royne et al., 2005).

Concentration of sunlight onto photovoltaic cells, and the consequent replacement of expensive photovoltaic area with less expensive concentrating device, is seen as one method to lower the cost of solar electricity. Because of the reduction in solar absorber area, more costly, but higher efficiency PV cells may be used. However, only a fraction of the incoming sunlight striking the cell is converted into electrical energy. The remainder of the absorbed energy will be converted into thermal energy in the cell and may cause the junction temperature to rise unless the heat is efficiently dissipated to the environment (Min et al., 2009; Mosalam Shaltout et al., 2000, 1994; Sabry et al., 2004).

The solar cell output is strongly related to its temperature as shown clearly in Eq. (1), which gives the  $I$ - $V$  characteristics of the solar cell especially at  $T > 300$  K according to the well-known one-diode model:

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### Nomenclature

$E_g$	band gap voltage	$R_t$	tube reflectivity
FR	flow rate	$R_{sc}$	solar cell reflectivity
$h_{ct}$	heat transfer coefficient	$T_t$	tube transmissivity
$I_{ph}$	photo-generated current	$T$	cell temperature
$I_0$	dark current	$V_{oc}$	open circuit voltage
$k$	Boltzmann's constant	$\eta$	electrical efficiency
$n$	ideality factor	$\phi$	the rotation rate tensor
$q$	electron charge	$\kappa$	turbulent kinetic energy
$R_s$	series resistance	$\varepsilon$	dissipation rate
$R_{sh}$	shunt resistance	$\rho$	density

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{q(V + R_s I)}{nkT} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (1)$$

$V_{oc}$  is related inversely to the cell temperature according to the differential Eq. (2) (Yoon and Garboushian, 1994):

$$\frac{dV_{oc}}{dT} = - \left[ \left( \frac{E_g}{q} - V_{oc} \right) + \frac{3kT}{q} \right] \cdot \frac{1}{T} \quad (2)$$

The important part of Eq. (2) is  $(E_g/q - V_{oc})$ . For high voltages, those are reached at high concentration levels,  $E_g$  stays nearly constant and  $V_{oc}$  increases. Thus, the temperature coefficient of  $V_{oc}$  decreases with increasing concentration. At one sun the temperature coefficient is around 1.7 mV/°C for highly efficient solar cells, at 200 sun the coefficient decreases to around 1.4 mV/°C (Yoon and Garboushian, 1994).

The concept of photovoltaic/thermal (PV/T) solar collector was first put forward by Kern and Russell (1978). The outcome brought a great lift to the overall efficiency of solar energy conversion (Ghitas, 2000; Ji et al., 2008; Sabry et al., 2004). This could be well established by the use of Fresnel lenses coupled to high efficiency solar cells. Thermal energy could be extracted from the back of the solar cell by means of active cooling subsystems in order to maintain its performance and use such thermal energy as well (Mosalam Shaltout and Ghitas, 1993). The cell efficiency varies with both temperature and concentration. There are various models for temperature and concentration dependency found in the literature (Edenburn, 1980; Florschuetz, 1975; Luque, 1989; Mbewe et al., 1985; O'Leary and Clements, 1980).

As shown in Fig. 1 (Royne et al., 2005), for monocrystalline Si solar cells, most of the models predict quite similar dependencies in the lower temperature range; most models assume straight lines. The different values predicted arise from the fact that monocrystalline Si solar cells have different peak efficiencies. Generally, the relation between cell efficiency with cell temperature is inversely proportional, especially at  $T > 300$  K.

As the solar cell performance is very sensitive to its operating temperature, active cooling, preferably by flowing water has to be applied especially at high concentration ratios in order to reduce the solar cell's temperature. On the other hand, thermal energy absorbed by water could be domestically used, adding to the total system efficiency.

In the past, few papers discussed economic evaluation of active cooled concentrator-photovoltaic systems e.g. (Kern and Russell, 1978; Sharan et al., 1985) considering a unique value of water flow rate without optimizing the cooling rate

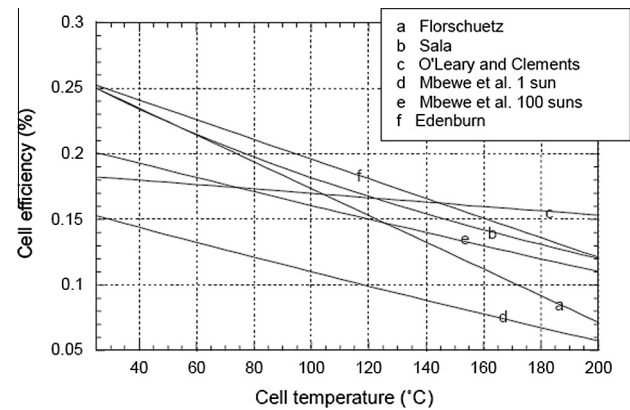
according to the incident illumination intensity and other system parameters.

In this study, a system consists of water passing through a copper tube. We propose a tube of length 1 m and four solar cells connected on top of the tube. Those cells are high-efficiency squared solar cells (~32%) with side length of 5 mm, in thermal contact with the tube's top centre, and exposed to concentrated solar radiation collected by Fresnel lenses, which is proposed. Flowing water aims at sufficiently cooling the four solar cells with a minimum water flow rate. The first solar cell will be highly cooled as it is in contact with flowing water near the inlet, while the 4th solar cell will be hot because water will be hot itself. System parameters such as concentration ratio and water flow rate are to be optimized in order to increase the solar cell electrical output, maximizing thermal gain, and in the same time, minimizing the energy consumed in the process of water pumping and circulation.

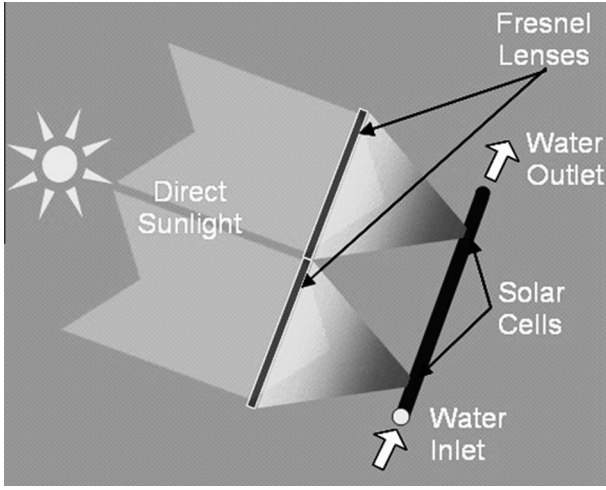
Fig. 2 shows schematic of a segment of a copper tube with solar cells thermally attached and exposed to concentrated solar radiation collected by Fresnel lenses. The whole system is proposed to be attached to a solar tracking subsystem to follow the sun during the operating hours.

## 2. System design and simulation technique

Detailed analysis of conductive and convective heat transfer processes occurring within the system containing the tube,



**Figure 1** Dependence of cell efficiency on cell temperature and illumination intensity (Royne et al., 2005).



**Figure 2** Solar cells running under concentrated solar radiation and actively cooled with water passing through a tube in thermal contact with the cells.

the solar cells, and flowing water in contact with the tube interior has been carried out employing finite volume algorithm. Radiative heat transfer between the solar cell and different objects in the system has not been included in the simulation process since it plays a limited role in reducing cell temperature due to its small area and accordingly very low view factor values; besides it requires full optimization of the system including the Lenses and external cover sizes – a task that is not dealt with in this work. Simulations were performed using a commercially available CFD package – a  $\kappa$ – $\varepsilon$  turbulence model with the two-layer approach – that is a two-equation model in which transport equations are solved for the turbulent kinetic energy  $\kappa$  and its dissipation rate  $\varepsilon$  is applied assuming a viscous sub layer (Han et al., 2009; Turan et al., 2012) that considers the viscous sub-layers with turbulent motion. The turbulent viscosity  $\mu_t$  is expressed as follows:

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \quad (3)$$

where  $C_\mu$  is a coefficient given by

$$C_\mu = \frac{1}{A_0 + A_s U^{(*)} \frac{k}{\varepsilon}} \quad (4)$$

$U^{(*)}$  is a function of strain rate tensor and vorticity tensor.  $A_0$  is value taken as 4.0.  $A_s$  is taken as  $(\sqrt{6}) \cos \phi$ .

The two-layer approach (Rodi, 1991) allows the  $\kappa$ – $\varepsilon$  model to be applied in the viscous sub layer. In this approach, the computation is divided into two layers. In the layer adjacent to the wall, the turbulent dissipation rate  $\varepsilon$  and the turbulent viscosity are specified as functions of wall distance. The values of  $\varepsilon$  specified in the near-wall layer are blended smoothly with the values computed from solving the transport equation far from the wall. The equation for the turbulent kinetic energy is solved in the entire flow. The model used has been verified against other work (Sabry et al., 2015, 2014). Physical parameters used during simulation processes are listed in Table 1. This simulation could be repeated to compare between system performances with different values of tube outer diameters and thicknesses.

**Table 1** List of the physical parameters used during simulation.

<i>Tube</i>	
Material	Copper
$h_{ct}$	50, 100 W/m <sup>2</sup> K
$R_t$	8%
Wall specification	Convection, surface to surface heat transfer
Length	1 m
Thermal specification	Smooth, no-slip
$T_t$	85%
External diameter	12 mm
Internal diameter	8 mm, 10 mm
<i>Solar cells</i>	
$\eta$	32%
$h_{ct}$	In-field calculated
Material	GaAsP/InGaAs QWSC
Side length	1 cm
$R_{sc}$	5%
Thermal specification	Convection, conduction, surface to surface heat transfer
$T_t$	0
<i>Flowing liquid</i>	
Type	Water
FR	0.0005 kg/s, 0.001 kg/s and 0.005 kg/s

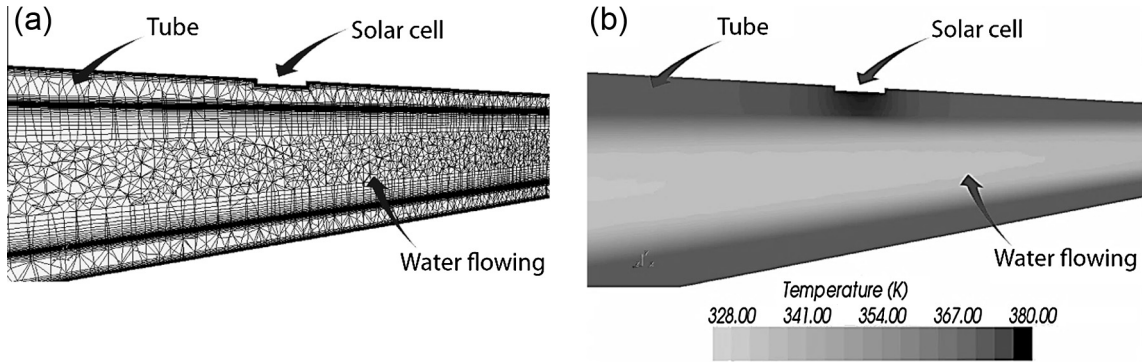
At first, the volume of the whole 3D geometry is meshed using a tetrahedral meshing after adjusting the volume mesh density. Boundary conditions listed in Table 1 are then applied to the system like inlet, outlet initial temperatures and incident radiation on the solar cells.

A three-dimensional, steady state model with turbulent flow has been used in the CFD simulation process. Iterations are initialized and started till it shows convergence after which the simulation stops giving predicted outlet and solar cells temperatures.

Fig. 3 shows a cross sectional plane of a segment of the geometry of the system showing the tube with water and one solar cell (a) after meshing the whole system and (b) temperature profile of the segment after running the simulation. In order to make sure that simulation results are independent of the mesh, a grid sensitivity study with different base-size and growth-rate meshes has been performed applying the physical parameters and boundary conditions listed in Table 1.

A series of simulations have been performed on two proposed tubes of copper, both of external diameter of 12 mm and side length of 100 cm. External diameters of the tubes are 8 mm and 10 mm respectively. Each tube is attached with four squared solar cells of side length 1 cm, equally spaced and thermally fixed on top of each of them. The solar cells are cooled by forcing water to pass inside the inner surface of each of the tubes. Each solar cell is assumed to be sited on focus of a squared Fresnel lens of side length 25 cm and receiving concentrated solar radiation on its full surface. Incident direct solar radiation on top of the Fresnel lens is assumed to be 800 W/m<sup>2</sup>.

Three different water flow rates of 0.0005, 0.001 and 0.005 kg/s respectively have been tested, each with four different optical concentration ratios of solar radiation incident on the solar cell 100, 200, 300 and 500× respectively.



**Figure 3** Cross sectional plane of a segment showing the tube with water and one solar cell (a) after meshing the whole system and (b) temperature profile of the segment after running the simulation.

Optical losses such as lens and solar cells reflectivity are not accounted on during the simulations.

The optical concentration ratio  $X$  is defined as follows:

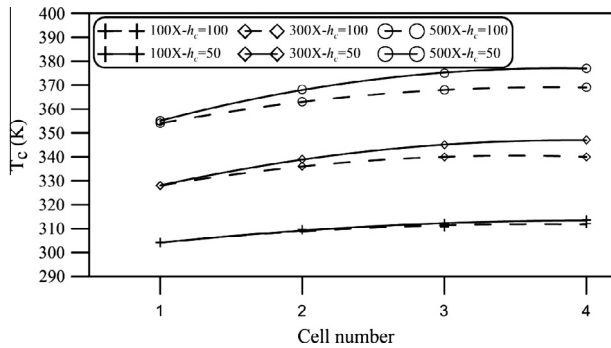
$$X = \frac{\text{Area of aperture}}{\text{Area of collector}} = \frac{A_{\text{lens}}}{A_{\text{cell}}} \quad (5)$$

In order to investigate the effect of changing speed of emerging water on solar cells and outlet temperatures, two different values of convective heat transfer coefficient  $h_c$  of 50 and 100 W/m<sup>2</sup>K respectively have been proposed between water and the inner surface of the tube.

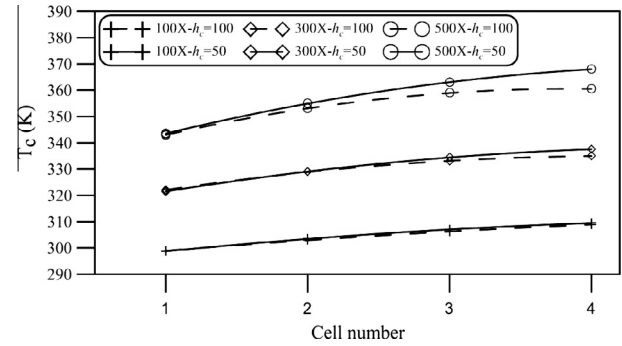
### 3. Simulation results

Effect of increasing water convective heat transfer is tested for the 8 mm internal diameter tube, at three different flow rates of 0.0005 kg/s, 0.001 kg/s and 0.005 kg/s that are shown in Figs. 4–6 respectively, and the solar cells temperatures are predicted accordingly. For the lowest water flow rate (0.0005 kg/s) consecutive solar cells temperatures increase gradually before showing asymptotic saturation while moving towards the outlet to reach about 370 °C for the 3rd and 4th cells at an optical concentration of 500×. Increasing  $h_c$  from 50 W/m<sup>2</sup>K to 100 W/m<sup>2</sup>K showed a significant effect of *reducing cells* temperatures especially the 3rd and 4th ones as shown in Fig. 4.

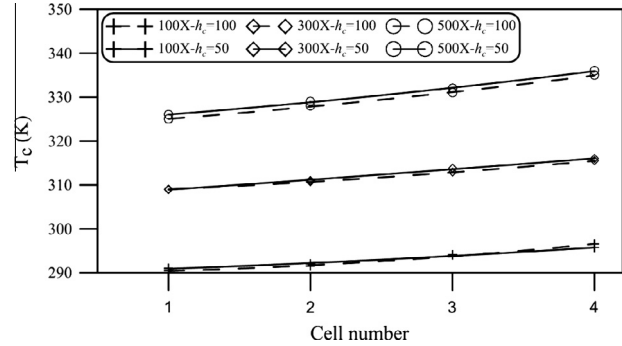
Effect of  $h_c$  is reduced with increasing water flow rate. Fig. 5 shows cells temperatures at the two abovementioned values of  $h_c$  at a flow rate of 0.001 kg/s. Almost no effect of



**Figure 4** Predicted cells temperatures as a function of optical concentration for the 8 mm internal diameter tube with  $h_c$  of 50 and 100 W/m<sup>2</sup>K respectively at a flow rate of 0.0005 kg/s.



**Figure 5** Predicted cells temperatures as a function of optical concentration for the 8 mm internal diameter tube with  $h_c$  of 50 and 100 W/m<sup>2</sup>K respectively at a flow rate of 0.001 kg/s.

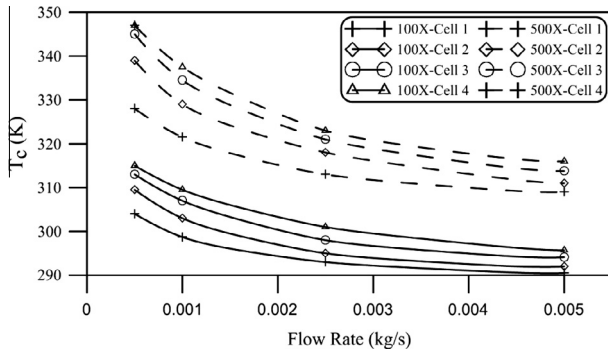


**Figure 6** Predicted cells temperatures as a function of optical concentration for the 8 mm internal diameter tube with  $h_c$  of 50 and 100 W/m<sup>2</sup>K respectively at a flow rate of 0.005 kg/s.

increasing  $h_c$  from 50 to 100 W/m<sup>2</sup>K is noticed at low concentration ratio, while a small effect is noticed at 500×. A further increase of water flow rate to about 0.005 kg/s was responsible for neglecting the effect of increasing  $h_c$  as shown in Fig. 6.

Increasing the rate of flowing water inside the tube has been investigated as shown in Fig. 7. Four different flow rates of 0.0005 kg/s, 0.001 kg/s, 0.0025 kg/s, and 0.005 kg/s are applied to the simulated system at a convective heat transfer coefficient  $h_c$  of 50 W/m<sup>2</sup>K, and the cell temperatures are predicted. Fig. 7 depicts the reduction of the cells temperatures of the 8 mm



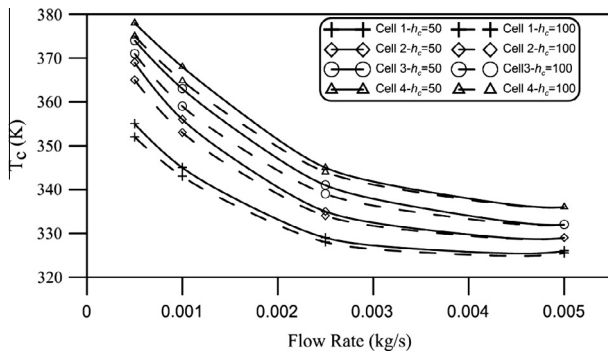


**Figure 7** Predicted cells temperatures as a function of water flow rate at an optical concentration ratio of 100 $\times$  and 500 $\times$  for the 8 mm internal tube diameter with  $h_c = 50$  W/m<sup>2</sup>K.

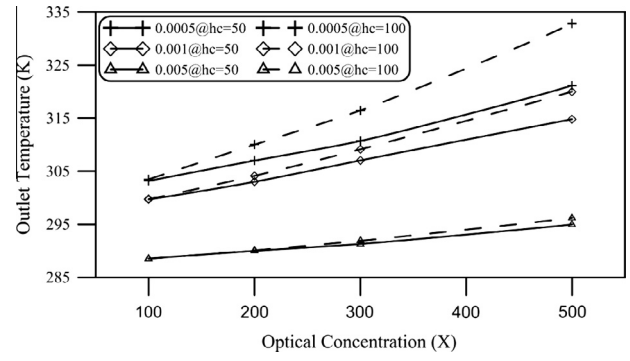
internal tube by increasing water flow rate for two optical concentration ratios namely 100 $\times$  and 500 $\times$ . An asymptotic decrease is observed with further increase in the flow rate indicating the insignificance of increasing flow rate on cooling solar cells. Also effect of increasing water flow rate at convective heat transfer coefficient of 50–100 W/m<sup>2</sup>K at an optical concentration ratio of 500 $\times$  has been investigated as shown in Fig. 8. It shows a decrease of cells temperatures especially at low flow rates, and its effect vanishes at higher flow rates.

Outlet temperature at a specific water flow rate increases by increasing the convective heat transfer coefficient as a result of increasing the heat collection, hence cooling efficiency. Fig. 9 shows the linear increase of the outlet temperature by increasing optical concentration ratio from 100 $\times$  to 500 $\times$  at the three flow rates. The figure also shows the increase in outlet temperature due to increasing the proposed convective heat transfer coefficient from 50 to 100 W/m<sup>2</sup>K, especially at high optical concentrations.

The increase of outlet temperature is almost linear with increasing optical concentration ratio. Rates of increasing outlet temperature are 0.045, 0.038 and 0.016 corresponding to FR of 0.0005 kg/s, 0.001 kg/s and 0.005 kg/s respectively at a convective heat transfer of 50 W/m<sup>2</sup>K. Increasing the convective heat transfer to 100 W/m<sup>2</sup>K results in increasing outlet temperature rates to be 0.074, 0.051, and 0.019 corresponding to FR of 0.0005 kg/s, 0.001 kg/s and 0.005 kg/s respectively.



**Figure 8** Predicted cells temperatures as a function of water flow rate at an optical concentration ratio of 500 $\times$  with  $h_c = 50$  and 100 W/m<sup>2</sup>K for the 8 mm internal tube diameter.



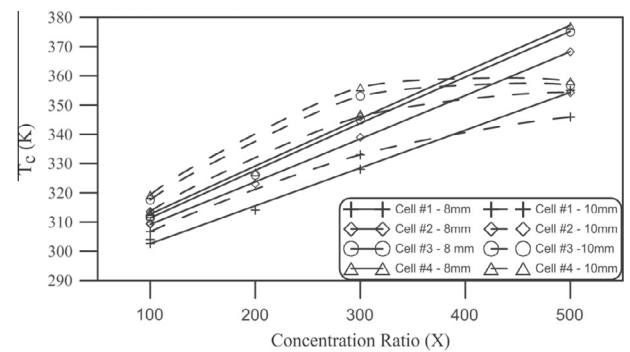
**Figure 9** Outlet temperature against optical concentration at different flow rates of 0.0005 kg/s, 0.001 kg/s, and 0.005 kg/s with  $h_c = 50$  and 100 W/m<sup>2</sup>K.

Fixing the external diameter at 12 mm and increasing the internal tube diameter from 8 to 10 mm, keeping water flow rate constant has a direct effect on the cells temperatures. Increasing the internal diameter has an advantage that it enables higher contact area between the tube's internal surface and the flowing water. On the other hand, reducing the internal diameter enables better dissipation of cells excessive heat in the copper bulk of the tube, acting like a passive cooling system beside heat removal by water cooling.

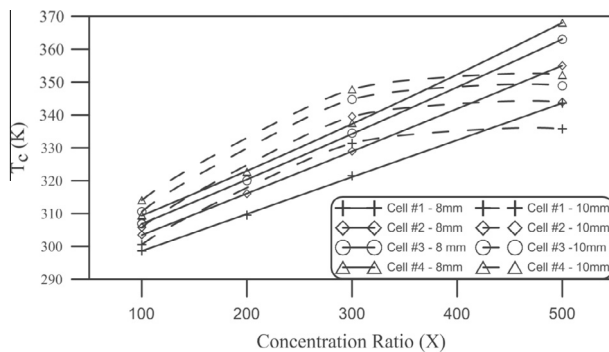
Two different tubes having the same external diameters of 12 mm and internal diameters of 8 mm and 10 mm were used in the simulated system, and the calculated cells temperatures were examined at flow rates of 0.0005, 0.001, 0.005 kg/s as shown in Figs. 10–12 respectively.

The following points arise when comparing amongst those graphs:

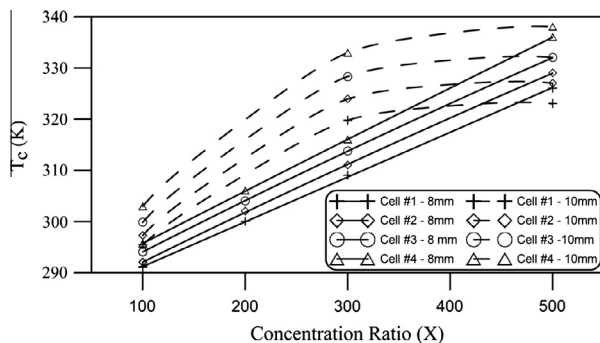
- 1- Generally, cells temperatures are lower at higher flow rates as expected.
- 2- For the 10 mm tube, a further increase of the concentration ratio over 300 $\times$  will not result in an increase of the cells temperature.
- 3- Cells fixed on top of the 10 mm tube's system are higher in temperature than that of the 8 mm diameter at low concentration ratios for all selected flow rates.



**Figure 10** Cells temperatures against optical concentration ratio for the internal tube diameters of 8 and 10 mm at water flow rate of 0.0005 kg/s.



**Figure 11** Cells temperatures against optical concentration ratio for the internal tube diameters of 8 and 10 mm at water flow rate of 0.001 kg/s.



**Figure 12** Cells temperatures against optical concentration ratio for the internal tube diameters of 8 and 10 mm at water flow rate of 0.005 kg/s.

- 4- Cells temperatures on top of the 8 mm tubes increase linearly, while those of the 10 mm tube show asymptotic increase at higher optical concentrations for all water flow rates.

#### 4. Conclusion

Effect of water cooling on solar cells operating at high concentration ratio is simulated using CFD. Two tubes having 12 mm external diameter and 8 mm and 10 mm internal diameters are investigated and compared. Different flow rates and optical concentration ratios are applied to the system. Also the effect of convective heat transfer coefficient on cells and outlet temperature is investigated at two values namely 50 and 100 W/m<sup>2</sup>K. It could be concluded that increasing convective heat transfer coefficient has a significant effect on reducing solar cells temperatures operating at low flow rates at high optical concentration ratios, especially with increasing the number of solar cells connected to the tube. Cells temperatures are expected to reach 370 K at an optical concentration ratio of 500× with the 8 mm tubes and a flow rate of 0.0005 kg/s. Increasing flow rates minimizes such effect of convective heat transfer coefficient. Cells temperatures are to be reduced to 335 K at same optical concentration with increasing flow rate to about 0.005 kg/s. Water flow rate of such system has to be determined precisely as its increase has a minor effect on cells temperatures.

On the other hand, widening internal diameter of the tube containing water reduces cells temperatures at higher optical concentration ratios and at low flow rates. In case of 0.0005 kg/s flow rate, cells temperatures might reach 380 K with the 8 mm tube, and reduce to about 360 K. In comparison, For higher flow rates (0.005 kg/s), cells temperatures are about 340 K, and reduced to only 337 K.

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