Three dimensional analysis of dye-sensitized, perovskite and monocrystalline silicon solar photovoltaic cells under non uniform solar flux

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Abstract

For low/high concentration, when the distribution of solar radiation is non-uniform over the surface of the solar cell, it gets heated up non-uniformly which affects the cell efficiency. Thus, in the present work, three dimensional analysis of the solar cells is carried out under non-uniform solar flux. It involves partial differential equations. For silicon cells, studies are available that use numerical techniques (involving iterations) to solve the differential equations. However, if the differential equations can be solved analytically, one can get an analytical expression for three dimensional non-uniform temperature distribution of the cell. The current work aims at it. Dye-sensitized (DSSC), perovskite and mono-Si cells are investigated. The effects of wind direction, its speed, inclination and solar irradiance on the three dimensional temperature distribution, heat losses and cell efficiency have been investigated. It is concluded that with increase in wind azimuthal from 0° to 90°, the efficiency decreases from 22.1% to 21.3% for mono-Si, 19.0% to 18.0% for perovskite and 12.0% to 11.9% for DSSC.

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37 **Nomenclature**

38	A_i	coefficient of Eq. 31 (K/m)
39	B_i	coefficient of Eq. 31 (K)
40	$C_{m,i}, D_{m,i}$	coefficients of Eq. 31 (K)
41	$E_{n,i}, F_{n,i}$	coefficients of Eq. 31 (K)
42	$G_{mn,i}, H_{mn,i}$	coefficients of Eq. 31 (K)
43	h	heat transfer coefficient due to convection (W/m ² K)
44	H	portion of solar irradiance leads to heat generation (W/m ²)
45	m	variable involved in Eq. 45
46	M	variable involved in Eq. 45
47	n	variable involved in Eq. 45
48	N	variable involved in Eq. 45
49	S	instantaneous solar-irradiance on cell (W/m ²)
50	U	overall coefficient for thermal loss (W/m ² K)
51	v_w	wind speed (ms ⁻¹)
52	α	variable involved in Eq. 28
53	β	variable involved in Eq. 28
54	β_p	angle of inclination of the system (rad)
55	γ	variable involved in Eq. 43
56	γ_w	wind-azimuthal (rad)
57	ε	emissivity for long wavelength radiation
58	$(\tau\alpha)$	transmittance-absorptance

1. Introduction

Advancements in solar photovoltaic proved it as an economically viable technology for electricity generation [1]. However, the cell efficiency is limited and it converts a small portion of the total irradiance into power [2]. A large portion of the irradiance leads to heat generation which affects the cell efficiency [3]. Thus, the thermal-electrical analysis of the cell needs to be carried out.

The studies that presented the one-dimensional analysis and experimental results for silicon solar cells are as follows: Goossens et al. [4] investigated the effect of wind speed on the electrical output. It was found that as wind speed decreases from 5m/s to 1m/s, the electrical efficiency decreases from 18.3% to 17.7%. Senturk [5] reported the effect of cloudy and partly-cloudy weather on the electrical output in comparison of clear-sky weather. A reduction of 9.7% was reported in case of partly-cloudy weather and 87.6% in case of cloudy weather. Gu et al. [6] investigated the effect of inclination on the electrical output. It was reported that the change of inclination from 10° to 70° resulting in the drop of electrical output by 20.7% due to decrease in the incident irradiance. Ceylan et al. [7] investigated the effect of solar irradiance, wind speed and ambient temperature on the panel temperature. It was found that as solar irradiance increases from 400W/m² to 800 Wm⁻², the panel temperature rises from 38.7 to 45.0°C. Vasel and Iakovidis [8] studied the effect of wind direction on the electrical output and found that the southerly winds increase the electrical output by 24%. The wind direction also affects the development of pressure field on the module [9]. Gu et al. [10] reported the electrical output for four different seasons: spring, summer, fall and winter. Ishii et al. [11] reported the temperature coefficients in order to calculate the effect of cell temperature on the electrical output. It was found that the electrical output of polycrystalline silicon cells decreases by 0.38% to 0.49% with increase in cell temperature by 1°C. Wang et al. [12] analysed the potential-induced degraded polycrystalline silicon modules and studied the effect of the cell temperature

on the electrical output. It was found that the electrical output decreases by 0.6051% /K - 0.8784% /K, the open circuit voltage decreases by 0.5411% /K - 0.7808% /K and the short circuit current increases by 0.0900% /K - 0.1148% /K.

For perovskite solar cells (PSC), Zhang et al. [13] reported that the cell efficiency decreases from 16% to 9% with rise in cell temperature from 300K to 360K. Cojocaru et al. [14] reported the decrease of efficiency from 13.5% to 6.1% with rise in cell temperature from 30°C to 90°C. Zandi et al. [15] investigated the heat distribution across the layers due to light absorption, non-radiative recombination and Joule heating and a COMSOL model [16] was also built to couple the optical, electrical and thermal characteristics.

Grätzel [17] observed that raising the temperature of DSSC from 20°C to 60°C has practically no effect on the power output. Raga et al. [18] also observed a stable performance of the DSSC power output with a slight peak at 30-40°C. On the other hand, Tripathi et al. [19] observed a significant effect of the cell temperature and solar irradiance level on the efficiency of the cell and found a decrease in the efficiency from 11% to 9.75% with an increase in cell temperature from 298K to 313K and increase in efficiency from 10% to 11% with an increase in irradiance level from 200W/m² to 800W/m². Sebastian et al. [20] also observed a decrease in efficiency from 7.7% to 6.2% with rise in cell temperature from 30°C to 70°C. Pettersson et al. [21] observed a decrease in power production of 16% with rise in cell temperature from 25°C to 60°C.

Studies have also been carried for two/ three dimensional analysis for silicon based cells. Chowdhury et al. [22] studied the effect of air gap underneath the module. It was found that the smaller air gap leads to lesser near-surface wind speed which can reduce the wind induced cooling and, thus, the electricity generation. Zhang et al. [23] studied the effect of non-uniformity of incident irradiance on the electrical efficiency. It was found that the electrical

efficiency decreases by 2.1% and the fill factor decreases by 2.6%. Yu et al. [24] developed two dimensional temperature-irradiance coupled model. It was found that the electrical efficiency decreases from 10.78% to 6.23% as shaded area increases from 0% to 80%. Ju et al. [25] investigated the effect of irradiance distribution on the electrical output. It was found that the inverse Gaussian distribution is better than the Gaussian distribution. Zhou et al. [26] investigated the effect of back sheet on the temperature distribution. Amanlou et al. [27] investigated different geometries of diffusers to achieve uniform temperature distribution over the air cooled PV panel. It was found that the diffuser with concave side walls can achieve more uniformity. The effect of air flow rate was also analysed and found that the increase in it from 0.008 to 0.016kg/s improved the electrical efficiency by 13.5%. Gallero et al. [28] investigated the effect of inclination angle on the temperature and velocity distributions. It was found that the system temperature decreases with increase in inclination. Pang et al. [29] investigated a ventilated photovoltaic module and compared against a closed one. It was found that an increase of 3.18% in the power output can be achieved using the ventilated one for a mass flow rate of 0.025kg/s and an increase of 6.06% can be achieved for 0.1kg/s. Noura and Sammouda [30] investigated the effect of dust deposition. It was found that a dust deposition density of 9g/m² can reduce the PV power output by 3W. Khanna et al. [31] reported that the external PV cooling is more effective for low wind speed conditions as compared to high wind speed conditions. For former case, the electricity generation of PV can be increased by 10.5% and for latter case, the increment can be 5.3% [32]. It has also been reported that the high wind speed can increase the duration of PV cooling [33].

It can be summarised that for perovskite cells and DSSC, only one-dimensional analysis had been carried out in literature considering uniform distribution of solar flux. However, for low/high concentration, the distribution of solar radiation will be non-uniform over the surface of the solar cell which had not been studied in literature yet. Under non-uniform distribution of

solar radiation, the cell will be heated up non-uniformly. Thus, three dimensional analysis is needed which has been carried out in the present work.

For silicon cells, it can be summarised that, in literature, the studies had been carried out for two and three dimensional analyses by using numerical techniques. An analytical expression for three dimensional temperature distribution of cells is not available in literature. It has been derived in the current work by solving the differential equations analytically.

The effects of working circumstances on the non-uniform 3-d temperature distributions, heat losses and efficiencies of the DSSC, perovskite and mono-Si cells are also investigated in the present work.

2. Modelling

In the presented work, Mono-si, DSSC and perovskite cells are investigated (Fig. 1). The dimensions of the cells are symbolized by L , w and t . Each cell consists of several layers. The mono-Si cell is made up of glass (1st layer), EVA (2nd layer), silicon (3rd layer), EVA (4th layer) and Tedlar (5th layer). DSSC is made up of glass (1st layer), dye-sensitized TiO₂ (2nd layer), electrolyte (3rd layer), platinum (4th layer) and glass (5th layer). Perovskite cell is made up of glass (1st layer), TiO₂ (2nd layer), perovskite (3rd layer), Spiro-OMeTAD (4th layer) and silver (5th layer). The temperature of each layer of solar cell is defined in Eq. (1) as follows

$$T(x, y, z) = \begin{cases} T_1(x, y, z) & \text{if } 0 \leq z \leq t_1 \\ T_2(x, y, z) & \text{if } t_1 \leq z \leq t_2 \\ T_3(x, y, z) & \text{if } t_2 \leq z \leq t_3 \\ T_4(x, y, z) & \text{if } t_3 \leq z \leq t_4 \\ T_5(x, y, z) & \text{if } t_4 \leq z \leq t_5 \end{cases} \quad (1)$$

Glass ($3 \times 10^{-3} \text{m}$)
 EVA ($5 \times 10^{-4} \text{m}$)
 Silicon ($3 \times 10^{-4} \text{m}$)
 EVA ($5 \times 10^{-4} \text{m}$)
 Tedlar ($1 \times 10^{-4} \text{m}$)

(a) Mono-Si cell

(b) Dye-sensitized cell

(c) Perovskite cell

Fig. 1 Cells considered in study

The following suppositions are made while carrying out the modelling

- (i) Due to negligible thickness, steady state analysis is carried out
- (ii) The contact resistances are not considered
- (iii) The incident solar flux follows the mirror symmetry around x axis and y axis

The heat generation (H) can be calculated using Eq. (2) by subtracting the electricity generation from the total absorbed irradiance as follows

$$H(x, y) = (\tau\alpha) S(x, y) - \eta_e S(x, y) \quad (2)$$

where η_e and S are the electricity generation efficiency and incident solar irradiance respectively.

To keep the mathematical solution of the equations simpler and to fit the same analytical equation for all types of cells, heat is considered to be generated at one particular surface for all types of cells. The interface of second and third layer of the cell is chosen. The generated heat enters the adjacent layers. Thus, the addition of the heat flowing towards upper and lower layers can be equated to the generated heat because of the steady state analysis and can be given by Eq. (3).

$$\left[k_2 \frac{\partial T_2}{\partial z} \text{ at } z=t_2 \right] + \left[-k_3 \frac{\partial T_3}{\partial z} \text{ at } z=t_2 \right] = H(x, y) \quad (3)$$

After entering the adjacent layers, heat flows via conduction. For any i^{th} layer, it can be given by Eq. (4).

$$\frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2} + \frac{\partial^2 T_i}{\partial z^2} = 0 \quad \forall i = 1 \text{ to } 5 \quad (4)$$

At the contact surface of the two layers, the heat going into one layer is equal to the heat going out of the other layer which can be given by Eq. (5).

$$k_i \frac{\partial T_i}{\partial z} \text{ at } z=t_i = k_{i+1} \frac{\partial T_{i+1}}{\partial z} \text{ at } z=t_i \quad \forall i = 1, 3 \text{ \& } 4 \quad (5)$$

At the contact surface of the two layers, the temperature of one layer is equal to the temperature of the other layer which can be given by Eq. (6).

$$T_i(x, y, z) \text{ at } z=t_i = T_{i+1}(x, y, z) \text{ at } z=t_i \quad \forall i = 1 \text{ to } 4 \quad (6)$$

From the front and rear of the cells, thermal energy is lost to the environment which can be given by Eqs. (7) and (8) respectively.

$$k_1 \frac{\partial T_1}{\partial z} \text{ at } z=0 = U_f [T_1(x, y, z) \text{ at } z=0 - T_a] \quad (7)$$

$$-k_5 \frac{\partial T_5}{\partial z} \text{ at } z=t_5 = U_r [T_5(x, y, z) \text{ at } z=t_5 - T_a] \quad (8)$$

where T_a is the ambient temperature. U_f and U_r are the overall coefficients for the thermal loss from the front and the rear of the cells respectively, which can be given by Eqs. (9) and (10).

$$U_f [T_{1,at \ z=0} - T_a] = h_f [T_{1,at \ z=0} - T_a] + \sigma \varepsilon_f F_{f_s} [T_{1,at \ z=0}^4 - T_s^4] + \sigma \varepsilon_f F_{f_g} [T_{1,at \ z=0}^4 - T_g^4] \quad (9)$$

$$U_r [T_{5,at \ z=t_5} - T_a] = h_r [T_{5,at \ z=t_5} - T_a] + \sigma \varepsilon_r F_{r_s} [T_{5,at \ z=t_5}^4 - T_s^4] + \sigma \varepsilon_r F_{r_g} [T_{5,at \ z=t_5}^4 - T_g^4] \quad (10)$$

The heat losses from the sides are neglected which can be given by Eqs. (11) and (12).

$$-k_i \frac{\partial T_i}{\partial x} \text{ at } x=\frac{L}{2} = k_i \frac{\partial T_i}{\partial x} \text{ at } x=-\frac{L}{2} = 0 \quad \forall i = 1 \text{ to } 5 \quad (11)$$

$$-k_i \frac{\partial T_i}{\partial y} \text{ at } y=\frac{w}{2} = k_i \frac{\partial T_i}{\partial y} \text{ at } y=-\frac{w}{2} = 0 \quad \forall i = 1 \text{ to } 5 \quad (12)$$

For most of the concentrators, the solar flux at front surface follows the mirror symmetry around x axis and y axis. Thus, the temperature of the cell will follow the same symmetry which can be given by Eqs. (13) and (14) as follows

$$T(x, y, z) = T(-x, y, z) \quad (13)$$

$$T(x, y, z) = T(x, -y, z) \quad (14)$$

The solution of Eq. (4) can be written in the following form (Eq. 15) using separation of variables [34].

Thus, for $i=L$,

$$T_1(x, y, z) = X_1(x) Y_1(y) Z_1(z) \quad (15)$$

Thus, for $i=L$, Eq. (4) can be written as Eq. (16).

$$Y_1 Z_1 \frac{\partial^2 X_1}{\partial x^2} + X_1 Z_1 \frac{\partial^2 Y_1}{\partial y^2} + X_1 Y_1 \frac{\partial^2 Z_1}{\partial z^2} = 0 \quad (16)$$

201 Dividing Eq. (16) by $X_I Y_I Z_I$ gives

$$202 \quad \frac{1}{X_1} \frac{\partial^2 X_1}{\partial x^2} + \frac{1}{Y_1} \frac{\partial^2 Y_1}{\partial y^2} + \frac{1}{Z_1} \frac{\partial^2 Z_1}{\partial z^2} = 0 \quad (17)$$

203 Since the boundaries are periodic in x and y directions, the solution follows cosine and sine functions in
 204 these directions. Thus, the first and second terms of the Eq. (17) are negative because only then the
 205 functions in x and y directions become cosine and sine. Thus, these can be given by Eqs. (18), (19) and
 206 (20).

$$207 \quad \frac{1}{X_1} \frac{\partial^2 X_1}{\partial x^2} = -\alpha^2 \quad (18)$$

$$208 \quad \frac{1}{Y_1} \frac{\partial^2 Y_1}{\partial y^2} = -\beta^2 \quad (19)$$

$$209 \quad \frac{1}{Z_1} \frac{\partial^2 Z_1}{\partial z^2} = \alpha^2 + \beta^2 \quad (20)$$

210 The solutions of Eqs. (18-20) are given by Eqs. (21), (22) and (23).

$$211 \quad X_1 = \begin{cases} c_1 x + c_2 & \text{if } \alpha = 0 \\ c_3 \cos \alpha x + c_4 \sin \alpha x & \text{if } \alpha \neq 0 \end{cases} \quad (21)$$

$$212 \quad Y_1 = \begin{cases} c_5 y + c_6 & \text{if } \beta = 0 \\ c_7 \cos \beta y + c_8 \sin \beta y & \text{if } \beta \neq 0 \end{cases} \quad (22)$$

$$213 \quad Z_1 = \begin{cases} c_9 z + c_{10} & \text{if } \alpha = \beta = 0 \\ c_{11} e^{-\sqrt{\alpha^2 + \beta^2} z} + c_{12} e^{\sqrt{\alpha^2 + \beta^2} z} & \text{if } (\alpha \neq 0) \text{ or } (\beta \neq 0) \text{ or } (\alpha \neq 0, \beta \neq 0) \end{cases} \quad (23)$$

214 Eqs. (13) and (15) give $X_I(x) = X_I(-x)$. Thus, Eq. (21) can be written as Eq. (24).

$$215 \quad X_1 = \begin{cases} c_2 & \text{if } \alpha = 0 \\ c_3 \cos \alpha x & \text{if } \alpha \neq 0 \end{cases} \quad (24)$$

216 Similarly, Eqs. (14) and (15) give $Y_I(y) = Y_I(-y)$. Thus, Eq. (22) can be written as Eq. (25).

$$Y_1 = \begin{cases} c_6 & \text{if } \beta = 0 \\ c_7 \cos \beta y & \text{if } \beta \neq 0 \end{cases} \quad (25)$$

Using Eqs. (15), (23), (24) and (25), $T_I(x,y,z)$ can be given by Eq. (26).

$$T_1(x, y, z) = \begin{cases} c_2 c_6 (c_9 z + c_{10}) & \text{if } \alpha = 0, \beta = 0 \\ (c_3 \cos \alpha x) c_6 (c_{11} e^{-\alpha z} + c_{12} e^{\alpha z}) & \text{if } \alpha \neq 0, \beta = 0 \\ c_2 (c_7 \cos \beta y) (c_{11} e^{-\beta z} + c_{12} e^{\beta z}) & \text{if } \alpha = 0, \beta \neq 0 \\ (c_3 \cos \alpha x) (c_7 \cos \beta y) (c_{11} e^{-\sqrt{\alpha^2 + \beta^2} z} + c_{12} e^{\sqrt{\alpha^2 + \beta^2} z}) & \text{if } \alpha \neq 0, \beta \neq 0 \end{cases} \quad (26)$$

Thus, by combining the constants, Eq. (26) can be written as Eq. (27).

$$T_1(x, y, z) = \begin{cases} A_1 z + B_1 & \text{if } \alpha = 0, \beta = 0 \\ \cos \alpha x (C_1 e^{-\alpha z} + D_1 e^{\alpha z}) & \text{if } \alpha \neq 0, \beta = 0 \\ \cos \beta y (E_1 e^{-\beta z} + F_1 e^{\beta z}) & \text{if } \alpha = 0, \beta \neq 0 \\ \cos \alpha x \cos \beta y (G_1 e^{-\sqrt{\alpha^2 + \beta^2} z} + H_1 e^{\sqrt{\alpha^2 + \beta^2} z}) & \text{if } \alpha \neq 0, \beta \neq 0 \end{cases} \quad (27)$$

Eqs. (11) & (27) give $\sin(\alpha L/2) = 0$ and Eqs. (12) & (27) give $\sin(\beta w/2) = 0$. Thus,

$$\alpha = \frac{2m\pi}{L} \text{ \& } \beta = \frac{2n\pi}{w} \quad \text{where } m \text{ \& } n \text{ are integers} \quad (28)$$

Thus, Eq. (27) can be written as Eq. (29).

$$T_1 = \begin{cases} A_1 z + B_1 & \text{if } m = 0, n = 0 \\ \cos \frac{2m\pi x}{L} \left(C_1 e^{-\frac{2m\pi z}{L}} + D_1 e^{\frac{2m\pi z}{L}} \right) & \text{if } m \neq 0, n = 0, m \text{ is integer} \\ \cos \frac{2n\pi y}{w} \left(E_1 e^{-\frac{2n\pi z}{w}} + F_1 e^{\frac{2n\pi z}{w}} \right) & \text{if } m = 0, n \neq 0, n \text{ is integer} \\ \cos \frac{2m\pi x}{L} \cos \frac{2n\pi y}{w} \left(G_1 e^{-\sqrt{\alpha^2 + \beta^2} z} + H_1 e^{\sqrt{\alpha^2 + \beta^2} z} \right) & \text{if } m \neq 0, n \neq 0, m, n \text{ are integers} \end{cases} \quad (29)$$

Thus, for $i=I$, the complete solution of Eq. (4) can be written as Eq. (30).

$$\begin{aligned}
227 \quad T_1(x, y, z) = & A_1 z + B_1 + \sum_{m=1}^{\infty} \left[\cos \frac{2m\pi x}{L} \left(C_{m,1} e^{-\frac{2m\pi z}{L}} + D_{m,1} e^{\frac{2m\pi z}{L}} \right) \right] \\
228 \quad & + \sum_{n=1}^{\infty} \left[\cos \frac{2n\pi y}{w} \left(E_{n,1} e^{-\frac{2n\pi z}{w}} + F_{n,1} e^{\frac{2n\pi z}{w}} \right) \right] \\
229 \quad & + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left[\cos \frac{2m\pi x}{L} \cos \frac{2n\pi y}{w} \left(G_{mn,1} e^{-\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} + H_{mn,1} e^{\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} \right) \right] \quad (30)
\end{aligned}$$

230 Similarly, for each i^{th} layer, the solution of Eq. (4) can be written as Eq. (31).

$$\begin{aligned}
231 \quad T_i(x, y, z) = & A_i z + B_i + \sum_{m=1}^{\infty} \left[\cos \frac{2m\pi x}{L} \left(C_{m,i} e^{-\frac{2m\pi z}{L}} + D_{m,i} e^{\frac{2m\pi z}{L}} \right) \right] \\
232 \quad & + \sum_{n=1}^{\infty} \left[\cos \frac{2n\pi y}{w} \left(E_{n,i} e^{-\frac{2n\pi z}{w}} + F_{n,i} e^{\frac{2n\pi z}{w}} \right) \right] \\
233 \quad & + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left[\cos \frac{2m\pi x}{L} \cos \frac{2n\pi y}{w} \left(G_{mn,i} e^{-\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} + H_{mn,i} e^{\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} \right) \right] \quad (31)
\end{aligned}$$

234 The constants A_i , B_i , $C_{m,i}$, $D_{m,i}$, $E_{n,i}$, $F_{n,i}$, $G_{mn,i}$ and $H_{mn,i}$ can be found out by using the following procedure.

235 Integration of the Eqs. (3), (5), (6), (7) and (8) from $x = -L/2$ to $L/2$ and from $y = -w/2$ to $w/2$ gives Eqs.

236 (A.1)-(A.10). By solving these ten Eqs. and using the fact that $\int_{-L/2}^{L/2} \cos \frac{2m\pi x}{L} dx = 0$ and

237 $\int_{-w/2}^{w/2} \cos \frac{2n\pi y}{w} dy = 0$, the expressions for A_i and B_i are obtained which are given in Eqs. (32)-(38) as

238 follows

$$239 \quad A_1 = \frac{\frac{1}{LW} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) dx dy \left[-\frac{t_2}{k_3} + \left(\frac{1}{k_3} - \frac{1}{k_4} \right) t_3 + \left(\frac{1}{k_4} - \frac{1}{k_5} \right) t_4 + \frac{t_5}{k_5} + \frac{1}{U_r} \right]}{k_1 \left[\left(\frac{1}{k_1} - \frac{1}{k_2} \right) t_1 + \left(\frac{1}{k_2} - \frac{1}{k_3} \right) t_2 + \left(\frac{1}{k_3} - \frac{1}{k_4} \right) t_3 + \left(\frac{1}{k_4} - \frac{1}{k_5} \right) t_4 + \frac{1}{k_5} t_5 + \frac{1}{U_f} + \frac{1}{U_r} \right]} \quad (32)$$

$$240 \quad A_2 = \frac{k_1}{k_2} A_1 \quad (33)$$

$$A_3 = \frac{1}{k_3} \left[k_1 A_1 - \frac{1}{LW} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) dx dy \right] \quad (34)$$

$$A_4 = \frac{1}{k_4} \left[k_1 A_1 - \frac{1}{LW} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) dx dy \right] \quad (35)$$

$$A_5 = \frac{1}{k_5} \left[k_1 A_1 - \frac{1}{LW} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) dx dy \right] \quad (36)$$

$$B_1 = \frac{k_1 A_1 + U_t T_a}{U_t} \quad (37)$$

$$B_i = B_{i-1} + (A_{i-1} - A_i) t_{i-1} \quad \text{for } i = 2 \text{ to } 5 \quad (38)$$

By multiplying the Eqs. (3), (5), (6), (7) and (8) with $\cos \frac{2m\pi x}{L}$ and integrating from $x = -L/2$ to $L/2$ and from $y = -w/2$ to $w/2$, Eqs. (B.1)-(B.10) are obtained. By solving these ten Eqs. and using the fact that $\int_{-L/2}^{L/2} \cos \frac{2m\pi x}{L} dx = 0$ and $\int_{-L/2}^{L/2} \left[\cos \frac{2m\pi x}{L} \right]^2 dx = \frac{L}{2}$, the expressions for $C_{m,i}$ and $D_{m,i}$ (for $i = 1$ to 5) are derived which are given in Eq. (39) as follows

$$\begin{bmatrix} C_{m,1} \\ C_{m,2} \\ C_{m,3} \\ C_{m,4} \\ C_{m,5} \\ D_{m,1} \\ D_{m,2} \\ D_{m,3} \\ D_{m,4} \\ D_{m,5} \end{bmatrix} = \begin{bmatrix} 0 & -k_2 e^{-\alpha t_2} & k_3 e^{-\alpha t_2} & 0 & 0 & 0 & k_2 e^{\alpha t_2} & -k_3 e^{\alpha t_2} & 0 & 0 \\ -k_1 e^{-\alpha t_1} & k_2 e^{-\alpha t_1} & 0 & 0 & 0 & k_1 e^{\alpha t_1} & -k_2 e^{\alpha t_1} & 0 & 0 & 0 \\ 0 & 0 & -k_3 e^{-\alpha t_3} & k_4 e^{-\alpha t_3} & 0 & 0 & 0 & k_3 e^{\alpha t_3} & -k_4 e^{\alpha t_3} & 0 \\ 0 & 0 & 0 & -k_4 e^{-\alpha t_4} & k_5 e^{-\alpha t_4} & 0 & 0 & 0 & k_4 e^{\alpha t_4} & -k_5 e^{\alpha t_4} \\ e^{-\alpha t_1} & -e^{-\alpha t_1} & 0 & 0 & 0 & e^{\alpha t_1} & -e^{\alpha t_1} & 0 & 0 & 0 \\ 0 & e^{-\alpha t_2} & -e^{-\alpha t_2} & 0 & 0 & 0 & e^{\alpha t_2} & -e^{\alpha t_2} & 0 & 0 \\ 0 & 0 & e^{-\alpha t_3} & -e^{-\alpha t_3} & 0 & 0 & 0 & e^{\alpha t_3} & -e^{\alpha t_3} & 0 \\ 0 & 0 & 0 & e^{-\alpha t_4} & -e^{-\alpha t_4} & 0 & 0 & 0 & e^{\alpha t_4} & -e^{\alpha t_4} \\ -(k_1 \alpha + U_f) & 0 & 0 & 0 & 0 & k_1 \alpha - U_f & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (k_5 \alpha - U_r) e^{-\alpha t_5} & 0 & 0 & 0 & 0 & -(k_5 \alpha + U_r) e^{\alpha t_5} \end{bmatrix}^{-1} \begin{bmatrix} P_m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (39)$$

where, α and P_m are given by Eqs. (28) and (40)

$$P_m = \frac{2}{\alpha L W} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) \cos \frac{2m\pi x}{L} dx dy \quad (40)$$

254 Similarly, by multiplying the Eqs. (3), (5), (6), (7) and (8) with $\cos \frac{2n\pi y}{L}$ and integrating from $x = -L/2$ to
 255 $L/2$ and from $y = -w/2$ to $w/2$, the expressions for $E_{m,i}$ and $F_{m,i}$ (for $i = 1$ to 5) are derived which are given
 256 in Eq. (41) as follows

$$257 \begin{bmatrix} E_{m,1} \\ E_{m,2} \\ E_{m,3} \\ E_{m,4} \\ E_{m,5} \\ F_{m,1} \\ F_{m,2} \\ F_{m,3} \\ F_{m,4} \\ F_{m,5} \end{bmatrix} = \begin{bmatrix} 0 & -k_2 e^{-\beta t_2} & k_3 e^{-\beta t_2} & 0 & 0 & 0 & k_2 e^{\beta t_2} & -k_3 e^{\beta t_2} & 0 & 0 \\ -k_1 e^{-\beta t_1} & k_2 e^{-\beta t_1} & 0 & 0 & 0 & k_1 e^{\beta t_1} & -k_2 e^{\beta t_1} & 0 & 0 & 0 \\ 0 & 0 & -k_3 e^{-\beta t_3} & k_4 e^{-\beta t_3} & 0 & 0 & 0 & k_3 e^{\beta t_3} & -k_4 e^{\beta t_3} & 0 \\ 0 & 0 & 0 & -k_4 e^{-\beta t_4} & k_5 e^{-\beta t_4} & 0 & 0 & 0 & k_4 e^{\beta t_4} & -k_5 e^{\beta t_4} \\ e^{-\beta t_1} & -e^{-\beta t_1} & 0 & 0 & 0 & e^{\beta t_1} & -e^{\beta t_1} & 0 & 0 & 0 \\ 0 & e^{-\beta t_2} & -e^{-\beta t_2} & 0 & 0 & 0 & e^{\beta t_2} & -e^{\beta t_2} & 0 & 0 \\ 0 & 0 & e^{-\beta t_3} & -e^{-\beta t_3} & 0 & 0 & 0 & e^{\beta t_3} & -e^{\beta t_3} & 0 \\ 0 & 0 & 0 & e^{-\beta t_4} & -e^{-\beta t_4} & 0 & 0 & 0 & e^{\beta t_4} & -e^{\beta t_4} \\ -(k_1 \beta + U_f) & 0 & 0 & 0 & 0 & k_1 \beta - U_f & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (k_5 \beta - U_r) e^{-\beta t_5} & 0 & 0 & 0 & 0 & -(k_5 \beta + U_r) e^{\beta t_5} \end{bmatrix}^{-1} \begin{bmatrix} Q_n \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (41)$$

258 where, β and Q_n are given by Eqs. (28) and (42)

$$259 \quad Q_n = \frac{2}{\beta L w} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) \cos \frac{2n\pi y}{L} dx dy \quad (42)$$

260 Similarly, by multiplying the Eqs. (3), (5), (6), (7) and (8) with $\cos \frac{2m\pi x}{L}$ and $\cos \frac{2n\pi y}{w}$ and integrating from
 261 $x = -L/2$ to $L/2$ and from $y = -w/2$ to $w/2$, the expressions for $G_{mn,i}$ and $H_{mn,i}$ (for $i = 1$ to 5) are derived
 262 which are given in Eq. (43) as follows

$$263 \begin{bmatrix} G_{mn,1} \\ G_{mn,2} \\ G_{mn,3} \\ G_{mn,4} \\ G_{mn,5} \\ H_{mn,1} \\ H_{mn,2} \\ H_{mn,3} \\ H_{mn,4} \\ H_{mn,5} \end{bmatrix} = \begin{bmatrix} 0 & -k_2 e^{-\gamma t_2} & k_3 e^{-\gamma t_2} & 0 & 0 & 0 & k_2 e^{\gamma t_2} & -k_3 e^{\gamma t_2} & 0 & 0 \\ -k_1 e^{-\gamma t_1} & k_2 e^{-\gamma t_1} & 0 & 0 & 0 & k_1 e^{\gamma t_1} & -k_2 e^{\gamma t_1} & 0 & 0 & 0 \\ 0 & 0 & -k_3 e^{-\gamma t_3} & k_4 e^{-\gamma t_3} & 0 & 0 & 0 & k_3 e^{\gamma t_3} & -k_4 e^{\gamma t_3} & 0 \\ 0 & 0 & 0 & -k_4 e^{-\gamma t_4} & k_5 e^{-\gamma t_4} & 0 & 0 & 0 & k_4 e^{\gamma t_4} & -k_5 e^{\gamma t_4} \\ e^{-\gamma t_1} & -e^{-\gamma t_1} & 0 & 0 & 0 & e^{\gamma t_1} & -e^{\gamma t_1} & 0 & 0 & 0 \\ 0 & e^{-\gamma t_2} & -e^{-\gamma t_2} & 0 & 0 & 0 & e^{\gamma t_2} & -e^{\gamma t_2} & 0 & 0 \\ 0 & 0 & e^{-\gamma t_3} & -e^{-\gamma t_3} & 0 & 0 & 0 & e^{\gamma t_3} & -e^{\gamma t_3} & 0 \\ 0 & 0 & 0 & e^{-\gamma t_4} & -e^{-\gamma t_4} & 0 & 0 & 0 & e^{\gamma t_4} & -e^{\gamma t_4} \\ -(k_1 \gamma + U_f) & 0 & 0 & 0 & 0 & k_1 \gamma - U_f & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & (k_5 \gamma - U_r) e^{-\gamma t_5} & 0 & 0 & 0 & 0 & -(k_5 \gamma + U_r) e^{\gamma t_5} \end{bmatrix}^{-1} \begin{bmatrix} R_{mn} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (43)$$

265 where, $\gamma = \sqrt{\alpha^2 + \beta^2}$ and α, β are given by Eq. (28) and R_{mn} is given by Eq. (44)

$$266 \quad R_{mn} = \frac{4}{\gamma L w} \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) \cos \frac{2m\pi x}{L} \cos \frac{2n\pi y}{L} dx dy \quad (44)$$

It is also found that, as m and n increase, the magnitudes of the terms inside the ‘summation bracket’ in Eq. (31) decrease. Thus, there is no need to sum up the terms to ∞ and there exists very small finite integers M and N such that, for $m > M$ and $n > N$, the terms inside the ‘summation bracket’ are negligible. Thus, Eq. (31) can be written as Eq. (45).

$$\begin{aligned}
T_i(x, y, z) = & A_i z + B_i + \sum_{m=1}^M \left[\cos \frac{2m\pi x}{L} \left(C_{m,i} e^{-\frac{2m\pi z}{L}} + D_{m,i} e^{\frac{2m\pi z}{L}} \right) \right] \\
& + \sum_{n=1}^N \left[\cos \frac{2n\pi y}{w} \left(E_{n,i} e^{-\frac{2n\pi z}{w}} + F_{n,i} e^{\frac{2n\pi z}{w}} \right) \right] \\
& + \sum_{m=1}^M \sum_{n=1}^N \left[\cos \frac{2m\pi x}{L} \cos \frac{2n\pi y}{w} \left(G_{mn,i} e^{-\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} + H_{mn,i} e^{\sqrt{\frac{m^2}{L^2} + \frac{n^2}{w^2}} 2\pi z} \right) \right] \quad (45)
\end{aligned}$$

The above equation is the general solution of Eq. (4). A_i , B_i , $C_{m,i}$, $D_{m,i}$, $E_{n,i}$, $F_{n,i}$, $G_{mn,i}$ and $H_{mn,i}$ are given in Eqs. (32)-(39), (41) and (43).

3. Validation

A numerical technique (using iterations) has been presented by Bonacina and Comini [35] for calculating the three dimensional temperature distribution. For validation purpose, the results are computed using the methodology of the current work and compared with their methodology. The parameters used are $\beta_p = 45^\circ$, $\gamma_w = 0^\circ$, $T_a = 30^\circ\text{C}$ and $v_w = 1\text{m/s}$ and the distribution of solar radiation over the top surface of the silicon cell considered for the calculations is plotted in Fig. 2. The temperature distribution over the surface of the cell calculated using the proposed methodology is plotted in Fig. 3 along with that of Bonacina and Comini [35]. The results show that the values computed using the analytical expression (Eq. 45) differ from those of Bonacina and Comini [35] by less than 1.2°C .

285
286 *Fig. 2 The distribution of solar radiation over the top surface of the cell considered for the calculations*

(a) Current Work

(b) Bonacina and Comini [35]

(c) Difference of temperature values (at $y = 0$) between plot (a) and plot (b)

Fig. 3 Comparison of the temperature distribution computed using analytical expression of current work with that of Bonacina and Comini [35]

4. Results and Discussion

In the current work, the studied cells are made to undergo various wind-azimuthal, wind speeds and inclination of system. The non-uniform temperature distributions and the corresponding cell efficiencies are computed. The specifications of the studied cells are given in Table 1.

Table 1 Specifications of studied cells

	Mono-Si	DSSC [19]	Perovskite [13]
Name and thickness of first covering	Glass (3mm)	Glass (3mm)	Glass (3mm)
Name and thickness of second covering	EVA (0.5mm)	Dye-sensitized TiO ₂ (12μm)	TiO ₂ (300nm)
Name and thickness of third covering	Silicon (0.3mm)	Electrolyte (2μm)	Perovskite (250nm)
Name and thickness of fourth covering	EVA (0.5mm)	Platinum (300nm)	Spiro-OMeTAD (100nm)
Name and thickness of fifth covering	Tedlar (0.1mm)	Glass (3mm)	Silver (1μm)
Efficiency Correlation	25.3 [1- 0.0045 (T _{avg} -25) + 0.085 ln (S/1000)]	11.9 [1- 0.001 (T _{avg} -40) + 0.057 ln (S/800)]	22.1 [1- 0.0068 (T _{avg} -27) + 0.085 ln (S/1000)]

4.1 Effect of Wind Direction on Heat Losses

The effect of wind direction on the heat losses (from the front surface of the cells) is shown in Fig. 4 keeping $\beta_p = 45^\circ$, $v_w = 4\text{m/s}$, and $S = 1000\text{W/m}^2$. It can be seen that as wind-azimuthal angle decreases from 90° to 0° , the heat loss from the front of the cell increases from 371 to 472W/m^2 for mono-Si cell, 314 to 407W/m^2 for DSSC and 279 to 358W/m^2 for perovskite. This effect can be explained as follows: when wind-azimuthal angle is high, the wind strikes the surface almost tangentially as shown in Fig. 5a. On the other hand, when wind azimuth angle is low, the wind strikes the surface almost normally (perpendicularly) as shown in Fig. 5b. Thus, for former case, the projected surface area coming in the path of wind is lesser as compared to the latter case of low wind azimuth angle. The lesser projected surface area in the path of wind leads to lesser heat transfer from the surface of the cell to the surroundings resulting in lesser heat losses which can also be seen from the results of Khanna et al. [31].

Fig. 4 Effect of wind direction on the heat losses from the front of the cells

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Fig. 5 (a) Case of high wind azimuth angle and (b) case of low wind azimuth angle

4.2 Effect of Wind Speed on Heat Losses

The effect of wind speed on the heat losses from the front surface of the cells is shown in Fig. 6 keeping $\beta_p = 45^\circ$, $\gamma_w = 0^\circ$ and $S = 1000\text{W/m}^2$. It can be seen that as wind speed increases from 0.2m/s to 5m/s, the heat loss from the cell increases from 445W/m² to 473W/m² for mono-Si cell, 377W/m² to 409W/m² for DSSC and 341W/m² to 359W/m² for perovskite. It is due to the fact that as the wind speed increases, the rate of wind hitting the surface increases as shown in Fig. 7. It increases the effect of forced convection. Thus, as the wind speed increases, the rate of heat transfer (from the surface of the cell to the surroundings) increases which leads to higher heat losses from the cell which can also be seen from the results of Armstrong and Hurley [36].

Fig. 6 Effect of wind speed on the heat losses from the front of the cells

Fig. 7 (a) Case of low wind speed and (b) case of high wind speed

4.3 Effect of Inclination Angle on Heat Losses

The effect of inclination angle on the heat losses from the front surface of the cells is shown in Fig. 8 keeping $\gamma_w = 0^\circ$, $v_w = 4\text{m/s}$ and $S = 1000\text{W/m}^2$. It can be seen that as inclination angle decreases from 90° to 0° , the heat loss from the cell decreases from 486 to 391W/m^2 for mono-Si cell, 419 to 331W/m^2 for DSSC and 368 to 294W/m^2 for perovskite. This effect can be explained as follows: when inclination angle of the system is very high, the wind hits the surface almost normally (perpendicularly) as shown in Fig. 9a. On the other hand, when inclination angle is low, the wind hits the surface almost tangentially as shown in Fig. 9b. Thus, for former case, the projected surface area coming in the path of wind is larger as compared to the latter case of low inclination angle. The larger projected surface area in the path of wind leads to higher rate of heat transfer from the surface of the cell to the surroundings resulting in higher heat losses which can also be seen from the results of Gallero et al. [28].

Fig. 8 Effect of inclination angle on the heat losses from the front of the cells

(a)

(b)

353

354

Fig. 9 (a) Case of high inclination angle and (b) case of low inclination angle

4.4 Effect of Solar Irradiance on Heat Losses

The effect of solar irradiance on the heat losses from the front surface of the cells is shown in Fig. 10 keeping $\gamma_w = 0^\circ$, $v_w = 4\text{m/s}$ and $\beta_p = 45^\circ$. It can be seen that as solar irradiance increases from 250 to 1000W/m^2 , the heat loss from the cell increases from 129W/m^2 to 472W/m^2 for mono-Si cell, 111W/m^2 to 407W/m^2 for DSSC and 99W/m^2 to 358W/m^2 for perovskite. Thus, the heat loss increases with increase in solar irradiance which can also be seen from the results of Armstrong and Hurley [36]. It is due to the fact that as the irradiance increases, the rate of solar energy absorption by the cell increases. It also increases the portion of solar energy that does not convert into electricity which increases the rate of heat generation in the cell resulting in higher heat losses.

Fig. 10 Effect of solar irradiance on the heat losses from the front of the cells

4.5 Effect of Wind Direction on Cell Temperature

The effect of wind direction on the temperature distributions is shown in Fig. 11 keeping $\beta_p = 45^\circ$, $S = 1000\text{W/m}^2$ and $v_w = 4\text{m/s}$. The corresponding variations in the maximum temperature of the cells are plotted in Fig. 12. It can be seen that as azimuthal rises to 90° , the maximum temperature point on the surface of the cell rises from 66 to 75°C for mono-Si cell, 61 to 68°C for DSSC and 56 to 64°C for perovskite. Thus, the cell temperature increases with increase in wind-azimuthal which can also be seen from the results of Vasel and Iakovidis [8]. It is due to the fact that when wind-azimuthal is very high, the heat losses from the cells are lesser which can be seen from Fig. 4. Thus, larger wind azimuthal leads to larger accumulation of heat in the cell resulting in higher cell temperature.

(a) Monocrystalline silicon solar cell

(b) Dye-sensitized solar cell

(c) Perovskite solar cell

Fig. 11 Effect of wind direction on the temperature distributions of the cells

Fig. 12 Effect of wind direction on the maximum temperature over the cells

4.6 Effect of Wind Speed on Cell Temperature

The effect of wind speed on the temperature distributions is shown in Fig. 13 keeping $\beta_p = 45^\circ$, $S = 1000\text{W/m}^2$ and $\gamma_w = 0^\circ$. The corresponding variations in the maximum temperature of the cells are plotted in Fig. 14. It can be seen that as wind speed increases from 0.5m/s to 5m/s, the maximum temperature point on the surface of the cell drops from 79 to 64°C for mono-Si cell, 72 to 59°C for DSSC and 67 to 55°C for perovskite. Thus, the cell temperature decreases with increase in wind speed which can be seen from the results of Goossens et al. [4]. It is due to the fact that when wind speed is high, the heat losses from the cells are higher which can be seen from Fig. 6. Thus, higher wind speed leads to lesser accumulation of heat in the cell resulting in lower cell temperature.

(a) Monocrystalline silicon solar cell

(b) Dye-sensitized solar cell

(c) Perovskite solar cell

Fig. 13 Effect of wind speed on the temperature distributions of the cells

Fig. 14 Effect of wind speed on the maximum temperature over the cells

4.7 Effect of Inclination Angle on Cell Temperature

The effect of inclination angle on the temperature distributions is shown in Fig. 15 keeping $\beta_p = 45^\circ$, $S = 1000\text{W/m}^2$ and $\gamma_w = 0^\circ$. The corresponding variations in the maximum temperature of the cells are plotted in Fig. 16. It can be seen that as inclination angle raises to 90° , the maximum temperature point on the surface of the cell decreases from 74 to 64°C for mono-Si cell, 67°C to 59°C for DSSC and 63°C to 55°C for perovskite. Thus, the cell temperature decreases with increase in inclination angle which can also be seen from the results of Gallero et al. [28]. It is due to the fact that for higher inclination, the heat losses from the cells are higher which can be seen from Fig. 8. Thus, higher inclination angle leads to lesser accumulation of heat in the cell resulting in lower cell temperature.

(a) Monocrystalline silicon solar cell

Fig. 15 Effect of the inclination angle on the temperature distributions of the cells

Fig. 16 Effect of inclination angle on the maximum temperature over the cells

4.8 Effect of Solar Irradiance on Cell Temperature

The effect of solar irradiance on the temperature distributions is shown in Fig. 17 keeping $\beta_p = 45^\circ$, $S = 1000 \text{ W/m}^2$ and $\gamma_w = 0^\circ$. The corresponding variations in the maximum temperature of the cells are plotted in Fig. 18. It can be seen that as solar irradiance increases from 250 W/m^2 to 1000 W/m^2 , the maximum temperature point on the surface of the cell rises from 39°C to 66°C for mono-Si, 37°C to 61°C for DSSC and 36°C to 56°C for perovskite. Thus, the cell temperature increases with increase in solar irradiance. It is due to the fact that for higher solar irradiance, the heat generation in the cell is also higher. Thus, higher solar irradiance leads to larger accumulation of heat in the cell resulting in higher cell temperature.

(a) Monocrystalline silicon solar cell

(b) Dye-sensitized solar cell

(c) Perovskite solar cell

Fig. 17 Effect of the solar irradiance on the temperature distributions of the cells

Fig. 18 Effect of solar irradiance on the maximum temperature over the cells

4.9 Effect of Wind Direction on Efficiency

The effect of wind direction on the efficiency of the cells is shown in Fig. 19 keeping other parameters fixed. It can be seen that as wind-azimuthal increases from 0° to 90° , the efficiency decreases from 22.1% to 21.3% for mono-Si, 19.0% to 18.0% for perovskite and 12.0% to 11.9% for DSSC. Thus, the cell efficiency decreases with increase in wind-azimuthal. It is due to the fact that when wind-azimuthal is very high, the cell temperature is higher which can be seen from Fig. 12. Thus, larger wind azimuthal leads to larger accumulation of heat in the cell resulting in lesser cell efficiency.

Fig. 19 Effect of wind direction on efficiency

4.10 Effect of Wind Speed on Efficiency

The effect of wind speed on the efficiency of the cells is shown in Fig. 20 keeping other parameters fixed. It can be seen that as wind speed decreases from 5m/s to 0.2m/s, the efficiency decreases from 22.2% to 20.7% for mono-Si, from 19.2% to 17.3% for perovskite and from 12.1% to 11.9% for DSSC. Thus, the cell efficiency decreases with decrease in wind-speed. It is due to the fact that when wind speed is high, the cell temperature is lower which can be seen from Fig. 14. Thus, higher wind speed leads to lesser accumulation of heat in the cell resulting in higher efficiency.

Fig. 20 Effect of wind speed on the efficiency of the cells

4.11 Effect of Inclination Angle on Efficiency

The effect of inclination angle on the efficiency of the cells is shown in Fig. 21 keeping other parameters fixed. It can be seen that as inclination angle decreases from 90° to 0°, the efficiency decreases from 22.4% to 21.3% for mono-Si, 19.1% to 18.1% for perovskite and 12.1% to 12.0% for DSSC. It is due to the fact that when inclination angle is very high, the cell temperature is lower which can be seen from Fig. 16. Thus, higher inclination angle leads to lesser accumulation of heat in the cell resulting in higher efficiency.

Fig. 21 Effect of inclination on the efficiency of the cells

4.12 Effect of Solar Irradiance on Efficiency

The effect of solar irradiance on the efficiency of the cells is shown in Fig. 22 keeping other parameters fixed. It can be seen that as solar irradiance decreases from 1000W/m^2 to 100W/m^2 , the efficiency decreases from 22.1% to 20.0% for mono-Si, 19.0% to 17.5% for perovskite and 12.0% to 10.7% for DSSC. It is due to the fact that when solar irradiance is low, the current generation by cell is lesser and the cell temperature is also lower. However, the negative effect of lesser current generation on the cell efficiency dominates over the positive effect of lower cell temperature. Thus, lower solar irradiance leads to lesser efficiency.

Fig. 22 Effect of solar irradiance on the efficiency of the cells

486 5. Conclusions

487 Three dimensional analysis of DSSC, perovskite and mono-Si cells has been carried out under non-uniform
488 solar flux and an analytical expression is derived. Using the proposed analytical expression, the effects of
489 wind-azimuth angle, its speed, solar irradiance and inclination of the system on the temperature
490 distributions, heat losses and the efficiency of the cells are investigated. It is concluded that

491 (i) For perovskite, the increment in wind-azimuthal from 0° to 90° reduces the efficiency from 19.0 to
492 18.0% and increases the maximum temperature from 56°C to 64°C .

493 (ii) For mono-Si, the increment in wind-azimuthal 0° to 90° reduces the efficiency from 22.1 to 21.3%
494 and increases the maximum temperature from 66°C to 75°C .

495 (iii) For DSSC, the increment in wind-azimuthal 0° to 90° reduces the efficiency from 12.0 to 11.9% and
496 increases the maximum temperature from 61°C to 68°C .

497 (iv) For perovskite, the increment in wind speed 0.2 to 5m/s elevates the efficiency from 17.3% to 19.2%
498 and reduces the maximum temperature from 67°C to 55°C .

499 (v) For perovskite, the decrement in inclination 90° to 0° reduces the efficiency from 19.1% to 18.1% and
500 increases the maximum temperature from 55°C to 63°C .

501 (vi) For perovskite, the decrement in solar irradiance from 1000 to 100W/m^2 reduces the efficiency from
502 19.0% to 17.5%.

503 It is concluded that the optimum conditions for the operation of the solar cells are the wind direction from
504 south towards north, high wind speed and high solar irradiance.

505 Appendix A

506 *A.1 Equations to evaluate the constants A_i and B_i (for $i = 1$ to 5)*

$$507 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_2 \frac{\partial T_2}{\partial z} \text{ at } z=t_2 \right] dx dy + \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[-k_3 \frac{\partial T_3}{\partial z} \text{ at } z=t_2 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) dx dy \quad (A.1)$$

$$508 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_1 \frac{\partial T_1}{\partial z} \text{ at } z=t_1 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_2 \frac{\partial T_2}{\partial z} \text{ at } z=t_1 \right] dx dy \quad (A.2)$$

$$509 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_3 \frac{\partial T_3}{\partial z} \text{ at } z=t_3 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_4 \frac{\partial T_4}{\partial z} \text{ at } z=t_3 \right] dx dy \quad (A.3)$$

$$510 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_4 \frac{\partial T_4}{\partial z} \text{ at } z=t_4 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_5 \frac{\partial T_5}{\partial z} \text{ at } z=t_4 \right] dx dy \quad (A.4)$$

$$511 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_1(x, y, z)_{\text{at } z=t_1}] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_2(x, y, z)_{\text{at } z=t_1}] dx dy \quad (A.5)$$

$$512 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_2(x, y, z)_{\text{at } z=t_2}] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_3(x, y, z)_{\text{at } z=t_2}] dx dy \quad (A.6)$$

$$513 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_3(x, y, z)_{\text{at } z=t_3}] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_4(x, y, z)_{\text{at } z=t_3}] dx dy \quad (A.7)$$

$$514 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_4(x, y, z)_{\text{at } z=t_3}] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_5(x, y, z)_{\text{at } z=t_4}] dx dy \quad (A.8)$$

$$515 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_1 \frac{\partial T_1}{\partial z} \text{ at } z=0 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [U_f(T_{1,\text{at } z=0} - T_a)] dx dy \quad (A.9)$$

$$516 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[-k_5 \frac{\partial T_5}{\partial z} \text{ at } z=t_5 \right] dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [U_r(T_{5,\text{at } z=t_5} - T_a)] dx dy \quad (A.10)$$

517 Appendix B

518 *B.1 Equations to evaluate the constants $C_{m,i}$ and $D_{m,i}$ (for $i = 1$ to 5)*

$$519 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_2 \frac{\partial T_2}{\partial z} \text{ at } z=t_2 - k_3 \frac{\partial T_3}{\partial z} \text{ at } z=t_2 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} H(x, y) \cos \frac{2m\pi x}{L} dx dy \quad (B.1)$$

$$520 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_1 \frac{\partial T_1}{\partial z} \text{ at } z=t_1 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_2 \frac{\partial T_2}{\partial z} \text{ at } z=t_1 \right] \cos \frac{2m\pi x}{L} dx dy \quad (B.2)$$

$$521 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_3 \frac{\partial T_3}{\partial z} \text{ at } z=t_3 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_4 \frac{\partial T_4}{\partial z} \text{ at } z=t_3 \right] \cos \frac{2m\pi x}{L} dx dy \quad (B.3)$$

$$522 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_4 \frac{\partial T_4}{\partial z} \text{ at } z=t_4 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_5 \frac{\partial T_5}{\partial z} \text{ at } z=t_4 \right] \cos \frac{2m\pi x}{L} dx dy \quad (B.4)$$

$$523 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_1(x, y, z) \text{ at } z=t_1] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_2(x, y, z) \text{ at } z=t_1] \cos \frac{2m\pi x}{L} dx dy \quad (B.5)$$

$$524 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_2(x, y, z) \text{ at } z=t_2] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_3(x, y, z) \text{ at } z=t_2] \cos \frac{2m\pi x}{L} dx dy \quad (B.6)$$

$$525 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_3(x, y, z) \text{ at } z=t_3] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_4(x, y, z) \text{ at } z=t_3] \cos \frac{2m\pi x}{L} dx dy \quad (B.7)$$

$$526 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_4(x, y, z) \text{ at } z=t_4] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [T_5(x, y, z) \text{ at } z=t_4] \cos \frac{2m\pi x}{L} dx dy \quad (B.8)$$

$$527 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[k_1 \frac{\partial T_1}{\partial z} \text{ at } z=0 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [U_f(T_{1, \text{at } z=0} - T_a)] \cos \frac{2m\pi x}{L} dx dy \quad (B.9)$$

$$528 \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} \left[-k_5 \frac{\partial T_5}{\partial z} \text{ at } z=t_5 \right] \cos \frac{2m\pi x}{L} dx dy = \int_{-L/2}^{L/2} \int_{-w/2}^{w/2} [U_r(T_{5, \text{at } z=t_5} - T_a)] \cos \frac{2m\pi x}{L} dx dy \quad (B.10)$$

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