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Optimization of Air Gap Required Below Solar PV Modules, Mounted on Metal Sheet roof-tops, through Thermal Analysis and Experimental Verification.

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ABSTRACT: The Solar PV Module panel efficiency is affected negatively by its temperature increase. On the PV Modules installed in open atmosphere for power generation, Natural cooling effect benefits considerably to maintain panel efficiency & hence improve plant generation output. The heat loss from the PV Module is through conduction to roof, heat carried away through convection by surrounding air & radiation to roof sheet or to sky. Here the module to sheet-roof gap plays an important role to ensure convective cooling on lower surface of modules. A thermal analysis is made to arrive at optimum air gap. The phenomenon of heat transfer is analysed from basic principles & a conclusion is arrived at optimised gap to be between 100mm to 110mm, beyond which the benefits are negligible. And any attempt to provide higher air gap will have increased bending load on mountings, which is counter-productive on structural design.

KEYWORDS: Roof top Solar PV Plant, PV Module installation, Module gap, Sheet roof Solar mounting, Efficiency of roof top solar PV power plants.

NOTATIONS:

1. NOCT : Normal Operating Cell Temperature
2. STC: Standard Test Condition.
3. PV Module : Solar Photo Voltaic Module

I. INTRODUCTION

All Solar PV Modules will have a parameter indicated by the manufacturer called the “temperature coefficient”. The temperature coefficient represents the percentage at which the panel efficiency reduces at each increase in degree Celsius (°C). As the temperature of the solar panel increases, its output current increases exponentially, while the voltage output is reduced linearly. **Most standard panels have a ‘temperature coefficient of power’ between -0.2% /°C to -0.5%/°C.** In many instances, a solar cell can get as hot as 65°C, causing the panel to become less efficient and therefore produce less power.

For example:

Module	=	Eldora Grand Ultima Silver, Vikram Solar, 72-AAA-300-320Wp.
Tc of Power (Y)	=	- 0.409%/°C
NOCT	=	44°C ± 2°C, 800W/m ² , Amb. Temp. 20□, Wind speed 1m/s.
STC	=	1000 W/m ² irradiance, 25°C cell temperature, as per EN 60904-3.

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Site of installation	=	Bengaluru, India.	
Actual atm condition	=	30°C	
Solar irradiance	=	1000 W/m ²	
Module Temp = T _{mod}	=	T _{air} + (NOCT-20) * G / 800	----- (Ref-1)
	=	60°C	
Drop in power output	=	-14.315 %	

Though there are many more variables involved in deciding final power output, module temperature is a major contributor.

The parameters which affect the module temperature are the atmospheric temperature at the site considered and the type of panel installation. As we have no control over the atmospheric conditions, we focus here on the way the modules are installed on sheet roofs.

When solar panels are installed on a sheeted rooftop, they experience greater temperatures than the ambient temperature. Panels that are fixed parallel to the roof with little to no air-gap between the rooftop and panel are the least efficient and experience the greatest rise in temperature (~35°C), leading to lower power output. A typical long rail based system of roof-top installation will allow for a sufficient air-gap between the roof surface and the panel, allowing airflow to have a cooling effect on the panel.

Here a detailed thermal analysis is done on a typical roof top Solar Panel installation, to arrive at optimum air-gap and the same is verified experimentally.



Fig-1: Solar PV plant installation on industrial sheeted roof top

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Fig-2: Solar PV plant installation on domestic sheeted roof top.

II. SURVEY

The author as a regular Solar Power Plant design consultant, gets reports of varying power generation output from similarly designed plants. Though there are many reasons for variations, one obviously contributing parameter was found to be the air gap between PV module & the back sheet of roof top systems. Most of the module manufacturers indicate in their data sheet the required air gap. Large number of module data sheets were studied & tabulated. Though most of them suggest an optimum air gap of around 100mm, some indicate far different in both higher & lower sides. Then a heat balance study is made to arrive at optimum gap & the same is practically verified at the manufacturing facility of M/s SEG, Bengaluru.

III. HEAT BALANCE

A typical heat balance of an installed Solar PV Panel can be summarised as:

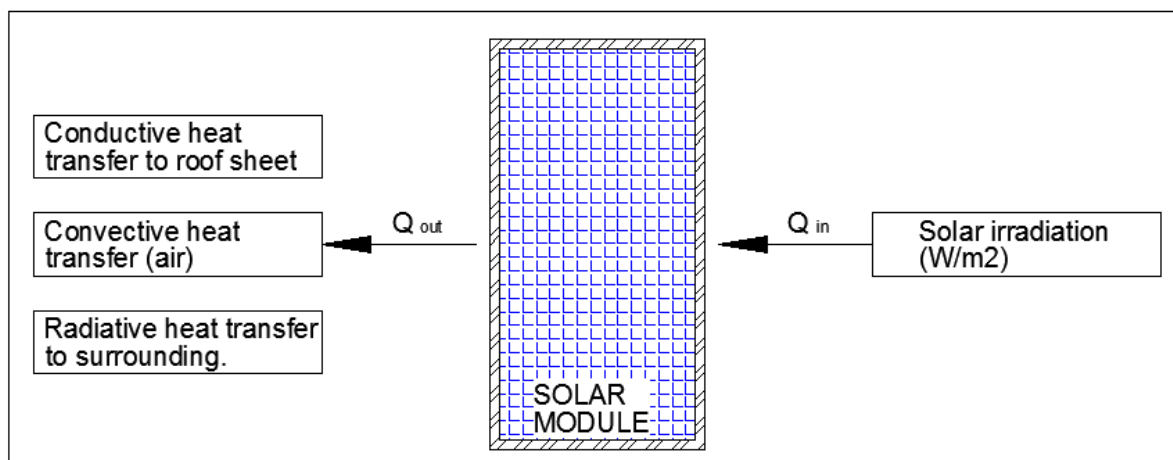


Fig-3: Heat balance for a typical roof mounted solar panel

The heat balance for the above considered example of a panel installed at site at Bengaluru, India, is considered for further analysis.

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Solar irradiance	=	1000 W/m ² (varies from 700W/m ² to 1000 W/m ² for the site considered)
Surface area of a module	=	1m X 2m = 2 m ²
Heat input to module (Q _{in})	=	2000 W
Roof sheet temperature	=	40 °C (assumed 10° above ambient).
Module mounting	=	Aluminium bracket, 4 sets of 40mm X 5mm & 100mm long.
Heat loss from the module =	=	Q _{out}

1. Conduction through mounting: Q_{out1}

$$Q_{\text{conduction}} = k * A/L * (T_h - T_c)$$

Where:

Q_{conduction} = quantity of heat flow. (W)

k = Thermal conductivity of the material. (W/m-K) (taken at 205 W/m-K for Aluminium)

A = sectional area (m²) (taken as 0.0008 m² as per input details)

L = Thickness (m) (taken as 100 mm as per input details)

T_h = Temperature of hot surface (K) (taken as 60+273= 333K, as per above calculations)

T_c = Temperature of cold surface (K) (taken as 40+273=313K, as per input details)

$$Q_{\text{out1}} = 32.8 \text{ W}$$

2. Convective heat loss from top surface of module: Q_{out2}

$$Q_{\text{convection}} = h * A * (T_s - T_a)$$

Where:

Q_{convection} = quantity of heat flow. (W)

h = Heat transfer coefficient. (W/m²-K) (taken at an assumed minimum air velocity of 2 m/s)

A = surface area (m²) (2 m²)

T_s = Temperature of hot surface (K) (taken as 60+273= 333K, as per above calculations)

T_a = Temperature of air (K) (taken as 30+273=303K, as per input details)

The heat transfer coefficient of air is a function of air velocity. For calculating this, a simplified empirical relationship equation is considered:

$$h = 10.45 - v + \sqrt{10 v} \text{ ----- (Ref-2, Eq-2)}$$

$$= 12.9 \text{ W/m}^2\text{-K}$$

Where, h is heat transfer co-efficient of air in W/m²-K at velocity v m/s.

$$Q_{\text{out2}} = 774 \text{ W}$$

3. Convective heat loss from bottom surface of module: Q_{out3}

As the heat transfer coefficient of air depends on the air velocity, here we have to find convective air velocity against a hot surface. We use the following empirical equation to calculate convective air velocity:

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$$V_c = 0.65 * [g * l * dt / (273 + t_e)]^{1/2} \text{ ----- (Ref-3)}$$

Where,

V_c = velocity in centre of airflow (m/s)

$g = 9.81$, acceleration of gravity (m/s²)

l = vertical distance from bottom (or top) of the surface (m) (2m from the above details)

$dt = t_e - t_s$ = temperature difference between surface and environment

t_s = surface temperature (°C) (60°C from the above details)

t_e = taken same as the atmospheric air temperature (°C) (30°C from the above details)

$$\Rightarrow V_c = 0.9 \text{ m/s}$$

As this velocity is < 2 m/s, we take the equation for Heat transfer co-efficient as:

$$h = 5.22 - 0.9 + \sqrt{10(0.9)} = 7.32 \text{ W/m}^2\text{-K}$$

$$Q_{\text{convection}} = h * A * (T_s - T_a)$$

$$\Rightarrow Q_{\text{out3}} = 439 \text{ W}$$

4. Radiation heat loss from top surface of module: Q_{out4}

Radiation heat loss from the top surface of the module can be treated as heat loss to sky.

$$Q_{\text{radiation}} = A \epsilon \sigma (T_s^4 - T_{\text{sky}}^4)$$

Where:

$Q_{\text{radiation}}$ = quantity of heat flow. (W)

ϵ = Emissivity of exposed surface. (taken at 0.9 for Glass)

A = sectional area (m²) (taken as 2 m² as per input details)

σ = Stefan-Boltzmann constant. ($5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4$)

T_s = Temperature of surface (K) (taken as 60+273= 333K, as per above calculations)

T_{sky} = Temperature of atmosphere, (K) (taken as 30+273=303K, as per input details)

$$\Rightarrow Q_{\text{out4}} = 394.7 \text{ W}$$

5. Radiation heat loss from bottom surface of module: Q_{out5}

Radiation heat loss from bottom surface of the module to surface of the sheet roof:

$$Q_{\text{radiation}} = A \epsilon_{\text{eff}} \sigma (T_1^4 - T_2^4)$$

Where:

$$\epsilon_{\text{eff}} = [1/\epsilon_1 + 1/\epsilon_2 - 1]^{-1}$$

ϵ_1 = Emissivity of roof sheet, taken as painted metal sheet at 0.8 (Ref appendix)

ϵ_2 = Emissivity of Toddler bottom surface of Module, taken at 0.8 (Ref appendix)

$$\Rightarrow \epsilon_{\text{eff}} = 0.66$$

A = sectional area (m²) (taken as 2 m² as per input details)

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σ = Stefan-Boltzmann constant. ($5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4$)

T_1 = Temperature of module surface (K) (taken as $60+273=333\text{K}$, as per above calculations)

T_2 = Temperature of roof sheet, (K) (taken as $40+273=313\text{K}$, as per input details)

$$\Rightarrow Q_{\text{out5}} = 204 \text{ W}$$

Total heat loss from the PV Module :

$$\begin{aligned} Q_{\text{out-tot}} &= Q_{\text{out1}} + Q_{\text{out2}} + Q_{\text{out3}} + Q_{\text{out4}} + Q_{\text{out5}} \\ &\Rightarrow 32 + 774 + 439 + 394 + 204 \\ &\Rightarrow 1843 \text{ W} \end{aligned}$$

As we can notice from the above heat balance calculation, the convective heat loss from the module due to air flow over the module surface forms about 65% of total heat loss.

HEAT LOSS FROM MODULE		
Conduction through mounting	2	%
Convection from top surface	42	%
Convection from bottom surface	24	%
Radiation from top surface	21	%
Radiation from bottom surface	11	%

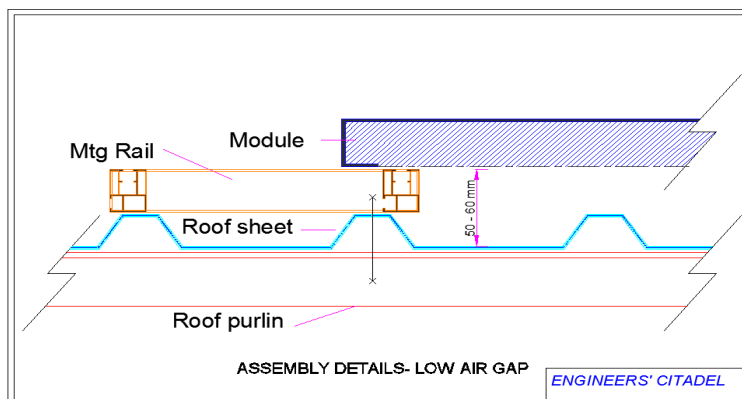


Fig-4: Module assembly with lower air gap.

When the modules are installed with an air gap of about 100mm from the sheet roof surface, the air below will experience a wind speed of convective wind velocity plus the acceleration caused by differential wind pressure and the atmospheric wind velocity.

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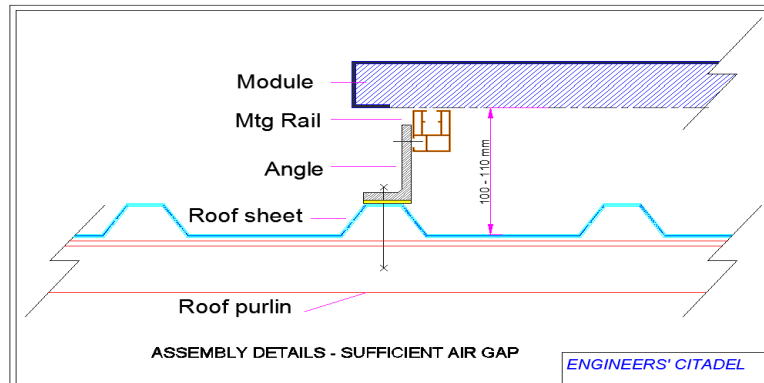


Fig-5: Module assembly with about 100mm air gap

In such an improved case of installation, the heat balance equation would get changed to:

Total heat loss from the PV Module=

$$Q_{out-tot} = Q_{out1} + Q_{out2} + Q_{out3} + Q_{out4} + Q_{out5}$$

$$=> 32 + 774 + 774 + 394 + 204$$

$$=> 2178 \text{ W}$$

This heat balance will ensure there is more heat loss than heat gain from solar irradiation. But any further increase in air gap will not provide benefit of heat loss proportionately. As this can be noticed from the curve of heat transfer coefficient versus air velocity gets almost horizontal.

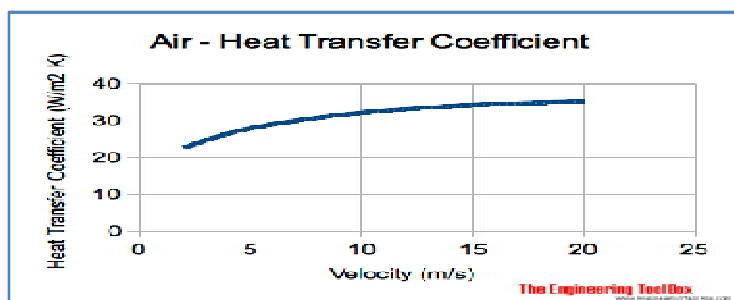


Fig-5: Graph of Heat Transfer Coefficient v/s air velocity.

IV. DRAUGHT INDUCED AIR VELOCITY

The analysis can also be done from the angle of natural draught of air flow below the modules. A typical A-type pitched roof with Solar PV Module fixed and given a air gap.

As we know from basic principles :

$$\text{Natural draught pressure (Pa)} = dp = g * h * (\rho_o - \rho_i)$$

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Where,

g = acceleration due to gravity (9.81 m/s²)

h = height in m

ρ_o = density of air out side the fluid path. (kg/m³)

ρ_i = density of air inside the fluid path. (kg/m³)

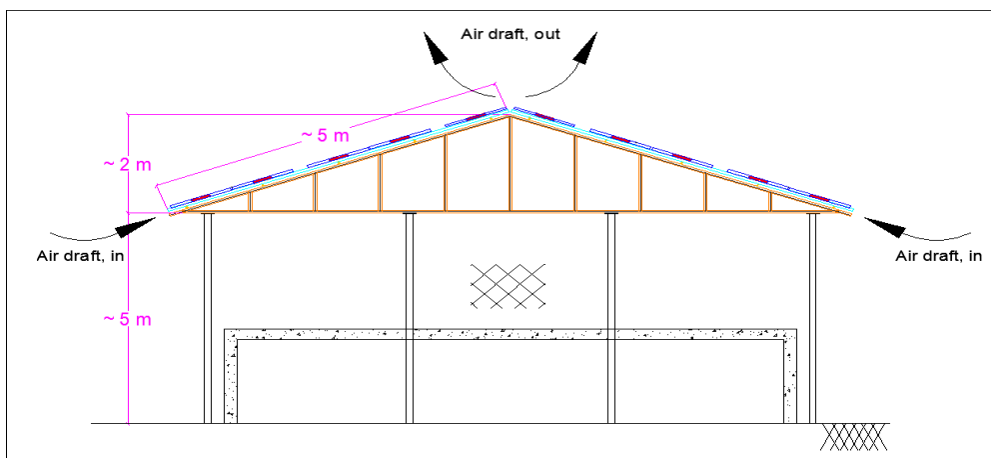


Fig-6: Typical A-type roof with PV Module installed on top.

The density of air is a function of temperature as per following equation:

$$\rho_t = \text{Density at temp } t = 1.293 * 273 / (273 + t)$$

$$\Rightarrow \rho_o = \text{density at temp } 30^\circ \text{ C} = 1.293 * 273 / (273+30) = 1.16 \text{ kg/m}^3$$

$$\Rightarrow \rho_i = \text{density at temp } 45^\circ \text{ C} = 1.293 * 273 / (273+45) = 1.10 \text{ kg/m}^3 \text{ (assuming the temperature of air which is between Module \& roof sheet as } 45^\circ \text{ C)}$$

$$\text{Natural draught pressure (Pa)} = dp = 9,81 * 5 * (1.16 - 1.10)$$

$$\Rightarrow 1.962 \text{ Pa}$$

The air velocity created due to this draught can be calculated using for following equation derived from Bernoulli's Equation:

$$V^2 = 2 dp / \rho_o$$

$$\Rightarrow 2 * 1.962 * 1.16$$

$$V = \Rightarrow 2.134 \text{ m/s}$$

So the minimum draught velocity the air in the passage between module & roof sheet achieves is more than 2m/s. This is maximum at a air gap of around 100mm and any higher gap will have lesser differential draught, due to lower temperature gradient and will not be beneficial.

So in conclusion the air gap between the modules & the roof sheet is best at about 100mm or it should be fully kept at higher elevation, more than about 300mm, when no draught effect will be available.

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But, for provision of higher gaps, the structure will transfer the moment to the fixing fasteners, which will have serious mechanical loads on the screws.

V. EXPERIMENTAL RESULTS

To verify experimentally the analysis made, 1 solar power plant is installed on the industrial roof top on a corrugated metal sheet roof. Three strings of 8 modules connected in series considered for experiment. Following are the details of experimental set up made on the roof of M/s SEG, Bengaluru.

Module : Eldora Grand Ultima Silver, Vikram Solar, capacity 300 Wp.

String : 3 strings each of 8 modules..

String capacity : $8 \times 300 \text{ Wp} = 2400 \text{ Wp}$.

Output connection : String out put is connected to a DC energy meter and then to load bus-bar.

Load : DC loads connected to bus bar. (DC fans & DC lights).

Surface area of each module : $1.96 \times 0.992 = 1.94 \text{ m}^2$

Total module area of one string : $8 \times 1.94 = 15.56 \text{ m}^2$.

Module efficiency : 15%

Performance ratio = $PR = (\text{Yield}) / (\text{Irradiance} \times \text{Module area} \times \text{Module efficiency})$

Period of experiment : 15 days from 2nd April till 16th April, 2017.

Following three sets of modules assembled:

1. SET-1: 8 module string with air gap of 40mm
2. SET-2 : 8 module string with air gap of 100mm
3. SET-3 : 8 module string with air gap of 160mm

The experiment was done for 15 days by recording readings every day on hourly basis, from 9AM till 4PM. The solar irradiation was recorded hourly & the cumulative units of power generated from each SET was recorded. The PR calculated & results tabulated.



Fig-7: Experimental set-up of 3 strings.

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Tabulation record of readings & results:

DAILY IRRADIANCE READING FROM METER (W/m ²)								
Time	9-10	10-11	11-12	12-1	1-2	2-3	3-4	Total
Day								
1	730	735	740	760	740	742	720	5167
2	731	737	741	762	772	745	721	5209
3	732	740	742	765	775	742	722	5218
4	731	737	741	762	772	744	721	5208
5	733	739	743	764	774	741	723	5217
6	733	736	743	761	771	743	723	5210
7	731	737	741	763	773	744	721	5210
8	732	739	742	764	774	742	722	5215
9	734	737	744	762	772	742	724	5215
10	733	736	743	761	772	741	723	5209
11	731	737	741	763	771	743	721	5207
12	734	737	744	763	773	743	724	5218
13	732	740	742	761	773	741	722	5211
14	735	737	745	762	771	742	725	5217
15	732	740	742	761	772	741	722	5210

The PR calculated and tabulated as below:

SET-1		SET-2		SET-3	
Daily yield	Daily PR	Daily yield	Daily PR	Daily yield	Daily PR
Wh	%	Wh	%	Wh	%
9202	76.30	9435	78.24	9464	78.48
9276	76.30	9510	78.22	9542	78.48
9291	76.29	9530	78.25	9555	78.46
9274	76.29	9510	78.24	9538	78.47
9290	76.29	9525	78.22	9550	78.43
9278	76.30	9515	78.25	9540	78.45
9276	76.28	9521	78.30	9541	78.46
9282	76.26	9524	78.25	9550	78.46
9281	76.25	9522	78.23	9548	78.44
9270	76.25	9515	78.26	9537	78.44
9270	76.28	9510	78.25	9538	78.48

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9288	76.26	9529	78.24	9557	78.47
9280	76.30	9518	78.26	9542	78.45
9290	76.29	9527	78.24	9553	78.45
9276	76.28	9515	78.25	9540	78.45
Av.PR	76.28	Av.PR	78.25	Av.PR	78.46

As can be observed from the results, the improvement in PR is :

Between SET-1 & SET-2 : air gap increase from 40mm to 100mm, PR increase 2.57%.

Between SET-2 & SET-3 : air gap increase from 100mm to 160mm, PR increase 0.27%.

VI. CONCLUSION

The installation of Solar PV modules on sheet roof is most ideal to have an air gap of 100mm to 110mm. Lower air gap will lead to increased module temperature, which will result in lower generation output. Higher than this dimension will have negligible cooling impact, but will have adverse effect of increased moment loads of fixing.

ACKNOWLEDGEMENT

The actual experimental set up was done under the guidance of Mr.Umasankar Reddy, a senior person with decades of experience in the field of Solar Power systems. Mr. T Satish Kumar gave the required permissions & enabled to conduct actual experiments on the roof top of M/s Surya Engineering Group, manufacturing unit at Bengaluru.

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