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Numerical Investigation of Drag and Lift Coefficient on a Fixed Tilt Ground Mounted Photovoltaic Module System over Inclined Terrain

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Abstract

The present study deals with the 2D and 3D steady state Reynolds-Averaged Navier-Strokes (RANS) simulations for the fixed tilt ground mounted photovoltaic (PV) module system by computational fluid dynamics (CFD). Here, we are considering shear stress transport k-omega (SST k-ω) turbulence model and the system is supposed to be immersed in atmospheric boundary layer (ABL). Initially the 2D and 3D numerical models are validated with the available experimental results of the literature. The work focuses on the evaluation of drag and lift coefficients on photovoltaic systems mounted over the inclined terrain (hills). Three different profile of hills were considered with height of 100m and ratio of height to length 0.5, 0.75 and 1 respectively over the consecutive seven rows of solar panel array. It is observed that with the increase in stiffness of hill, drag and lift forces increases respectively. So, implementation of solar panels on the stiff hills is not recommended. Also, the influence of panel length, spacing factor between consecutive panels, clearance height from the ground, wind speed and angle of tilt are studied parametrically.

Keywords: Wind loading, Photovoltaic panels, CFD.

I. INTRODUCTION

As per the electricity production and consumption is concerned, India stands third in the world. Out of total installed capacity of 26 GW (as on sept 2018), India is mostly relying on fossil fuels for the power production, specifically coal is being used on a large scale which in the year 2017-18 generated about three fourth of total electricity demand. In the present era of growing power demands, world is slowly moving toward the use of non-renewable energy sources like solar, wind, tidal, biomass, etc. As per as the India is concerned where sun is available throughout the year (most of the days in a year), the use of solar energy is increasing rapidly as we see past two-three years and there will be boom in the market for the upcoming decade. The photovoltaic (PV) modules are employed to convert the solar radiations into electric power and with the help of Inverter battery dc current is transformed into ac current.

The basic fundamental on which photovoltaic module work is photovoltaic effect i.e. as soon as the photons (packets of light energy) incident on the surface of photosensitive surface of PV module, electron-hole pair form and hence current flows through the circuit and electricity is stored in the battery. If we think about single solar module, it has limited power supply. So, for most of the applications multiple solar modules are employed. The rating of the solar module is done by its DC power output. So, the use of Photovoltaic models is increasing in domestic and the commercial sectors for the generation of electricity.

On the commercial scale, large size solar farms are being setup rapidly which requires enormous quantity of land and the supporting materials. As per as the cost of Photovoltaic solar module is concerned, the initial setup cost is quite high, so it become necessary to maintain the solar assembly and protect it from gust of wind, heavy rainfall, dust, etc. The most important load on the PV panels is because of wind. Forces acting on the surface of solar panels due to strong wind can be so severe, that it can blow away the entire module systems of the farm. So, it becomes necessary to study about the forces acting over the surface of the solar panels to ensure the safety against the strong wind.

In the past many studies and researches have been done to estimate the wind effects on photovoltaic (PV) panels. **G.T. Bitsumalik (2010)** evaluated the wind loads on ground mounted solar panels using Computational Fluid Dynamics (CFD) for the four different cases. He compared the numerical results obtained by the CFD with the previously done experimental results, and found good agreement. **C. Jubayer and H. Hagen (2012)** had done the numerical as well as experimental analysis of wind effects over solar panels. They varied the angle of attack of wind from 0 degree to 180 degree and calculated the coefficient of drag, lift and overturning moment.

M. Shademan (2014) carried out the numerical study of wind loading acting over ground mounted solar panels for different flow configurations. They concluded that the max force experienced by the ground mounted panel system is at 0 degree and 180 degree. They also studied about the effect of inter-row spacing gap on wind loading as well as the sheltering effect. **A.A.Ogedengbe (2013)** had done the experimental study of wind effect over the solar panels in which he made scaled aluminium model of solar panel on which wind tunnel experiment were carried out by using computerized data acquisition. They calculated pressure coefficient at various position of solar panel surface.

Warsido (2014) studied the sheltering effect i.e. effect of one solar panel over another consecutively placed solar panel. They carried out wind tunnel experiment to study the consecutive placement of solar panels along with different the spacing factors, both horizontal and lateral with inlet wind speed of 15m/s and angle of tilt 25°. As compared to Shademan and Hangan's study, here in warsido wind tunnel experiment a greater number of consecutively placed solar panels (15 panels) are used and different lateral spacings were also considered.

From the literature review it is seen that the force acting on the surface of solar panels depends on the direction of wind, wind speed, spacing factor between consecutive panels, etc. In the present literature review, low-rise, fixed tilt, ground mounted solar module is kept in consideration which is supposed to be immersed under the atmospheric boundary layer (ABL). There is no literature observed for the extreme high velocity flow (in the order of 30 m/s to 60m/s) analysis over the solar module system. Also, geographical topography-based investigation is not done by the researchers in the past.

II. PROBLEM DESCRIPTION

As we know, the gust wind destructs the solar panels heavily so it becomes prominent to study the gust wind effects over the arrays of solar panel. Present work focuses on the analysis of the wind loading effect on the solar panels caused by gust of wind. The size of single solar panel is 1600 x 1000 mm (standard size). The thickness of the solar panel can be varied between 30 to 100mm as per the literature, we have considered 50mm thick panels. There are seven side by side solar panels connected in series which makes the row length 7m. There are seven rows of solar panel arrange in parallel one above another with inter-row spacing gap of 2m. The angle of inclination of linear solar panel array is set to 25 Degree and ground clearance of 500mm is provided as shown in the figure.

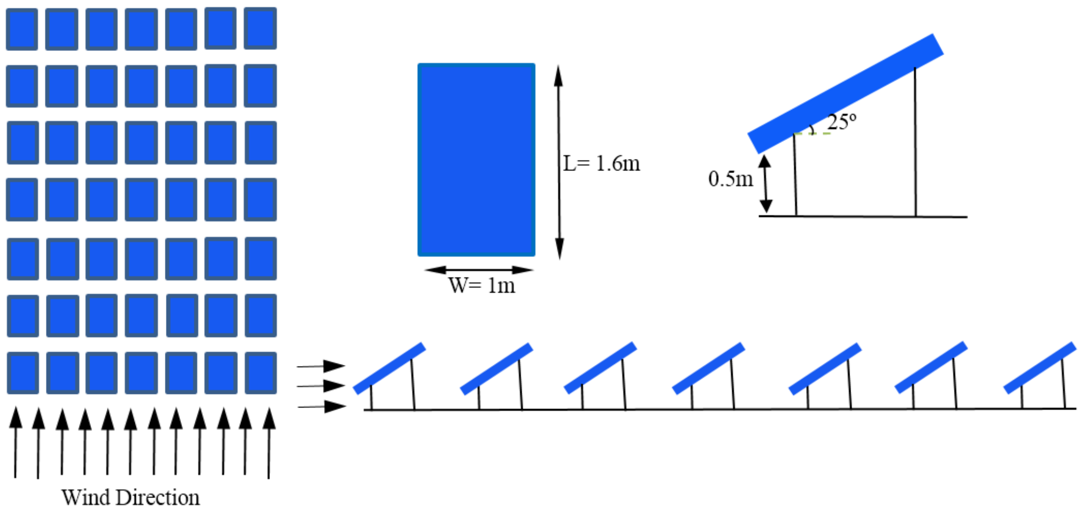


Figure1: *Array of ground mounted solar module assembly [Top view(left) and Side view(right)]*

So, the objective of the work is to analyse the effect of panel length, tilt angle, row spacing, ground clearance, and most importantly high order velocity of flow on wind loading over ground mounted solar module system. The second objective is to perform geographical topology-based investigation to evaluate the forces acting over the solar panel surface for gust wind flow.

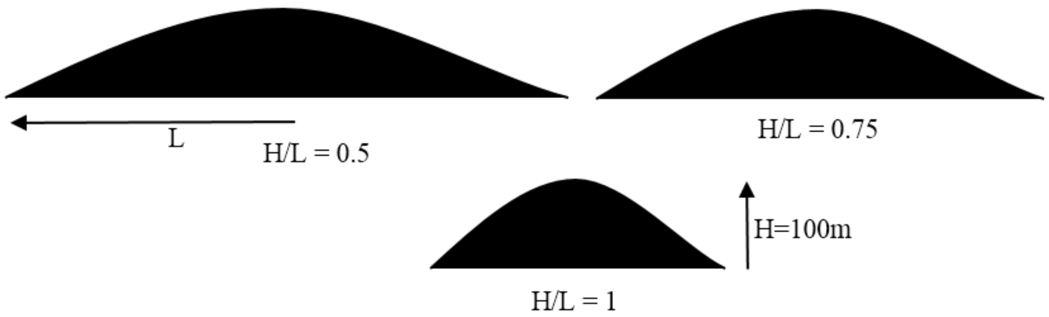


Figure 2: *Three different Hill profiles used for the present work analysis*

In the geographical topology-based investigation, the height of the hill is kept constant to 100 meters, while the length of the hill is varied so as to make the different hill profiles (fig). Here, in the present study we have considered three profiles of hill with H/L ratio of 0.5, 0.75 and 1 respectively.

III. METHODOLOGY

The flow of work for the Numerical simulations are split up into two parts:

Part A) Numerical investigation of solar panels mounted on planar surface.

I. Investigation over single ground mounted solar panel.

a. Validation   b. Tilt angle analysis

II. Investigation over array of ground mounted solar panel.

a. Panel length investigation   b. Spacing factor analysis

c. Effect of clearance height   d. High order velocity investigation

Part B) Numerical investigation of solar panels mounted on inclined surface.

I. Terrain Inclination Analysis   II. Geographical Topology-based investigation

IV. MATHEMATICAL MODEL

Computational Fluid Dynamics (CFD) is being used in the present study to analyse the flow behaviour of fluid (air) under the effect of different conditions. The Turbulence model used here in the present work is K-ω SST model under the steady state condition.

- **Conservation of mass:**

  $div(\rho u) = 0$

- **Conservation of momentum:**

  X-momentum equation

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

  Y-momentum equation

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = \rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right)$$

  Z-momentum equation

$$\rho\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)$$

Turbulence Model:

From the literature study it is observed that the physics of such wind flow over the solar panels has been successfully captured by using K-ω turbulence model.

Turbulent Kinetic Energy (k) Equation:

$$\frac{\partial}{\partial t}(\rho k) + div(\rho k U) = div\left(\Gamma_k grad\ k\right) + G_k - \rho\beta\omega 2 + S_k$$

$\Gamma_k = \mu + \frac{\mu_T}{\sigma_k}$ is turbulent diffusion coefficient of kinetic energy

$G_k = \mu_T\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}$ is rate of generation of turbulent energy

Specific rate of dissipation is given by following transport equation:

$$\frac{\partial}{\partial t}(\rho\omega) + div(\rho\omega U) = div\left(\Gamma_\omega grad\ \omega\right) + G_\omega - Y_\omega + S_\omega$$

$\Gamma_\omega = \mu + \frac{\mu_T}{\sigma_\omega}$ is turbulent diffusion coefficient of dissipation rate.

Boundary conditions:

Boundary condition for the present work investigation are as follows.

Inlet: At inlet velocity of the flow is assumed to be logarithmic in nature due to the expected turbulence cause by ground [reference]. It is given by, $U(y) = \frac{u_{ABL}^*}{k}\ln\left(\frac{y+y_0}{y_0}\right)$.

Other inputs is computed by, Kinetic Energy, $K(y) = \frac{u^{*2}{}_{ABL}}{\sqrt{C_\mu}}$, Specific Dissipation Rate : $\omega(y) = \frac{u^{*3}{}_{ABL}}{k(y+y_0)C_\mu K(y)}$ Where y is the height co-ordinate, roughness height y_0 =0.03m for open terrain,

u_{ABL}* the atmospheric boundary layer friction velocity, k the von Karman constant (0.40) and Cμ=0.09 a model constant for k and ε .

Outlet: Zero static pressure **Walls:** No slip – smooth wall.

Ground: No slip(roughness ks= 0.01m, Cs=0.5) **Other open boundaries:** Symmetry condition

V. NUMERICAL EXECUTION AND COMPUTATIONAL DOMAIN:

Turbulence Model used here is k-ω SST model for the steady state analysis. The domain is of size 34.5m X 23.2m X 9.2m in which solar panel is kept at 25 Degree inclined with mean height from the ground 1.1m. Size of solar panel is 2.4m X 7.2m and thickness is considered 50mm.

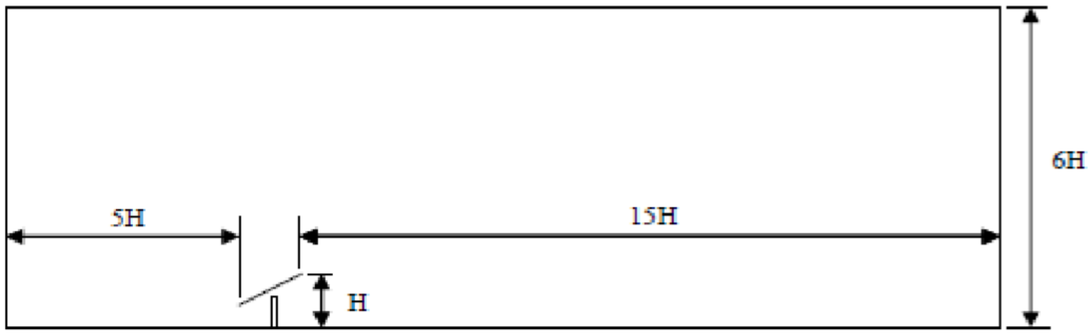


Figure 3: *Computational domain for the validation model.*

Fig.3 shows the domain specifications with H being the height of the object, 6H is the vertical height of the domain, 5H and 15H are the distances before and after the object. For the 3D modelling, the lateral distance between object and the domain is taken 5H on both sides. These specifications help to avoid the blockage effects while fluid(air) flowing through the domain.

V. RESULT

Part A) Numerical investigation of solar panels mounted on planar surface

I) Investigation over single ground mounted solar panel.

a. <u>Validating with Jubayer's Study</u>

In 2012 Jubayer done the numerical investigation as well as performed experiment to calculate wind loadings on ground mounted solar panel. In the model solar panel array of size 2.4m x 7.2m is used and the thickness of plate is taken 50mm.The tilt angle of solar panel is set to 25° with horizontal and clear height from the ground is 0.6m.

Jubayer used the Open FOAM CFD program for the analysis and the turbulence model selected is SST K-omega. The reference velocity taken is 17.5m/s at a height of 10m with 0.03m aerodynamics roughness length for open terrain. The wiremesh model for the 3D computational domain is shown in fig.4

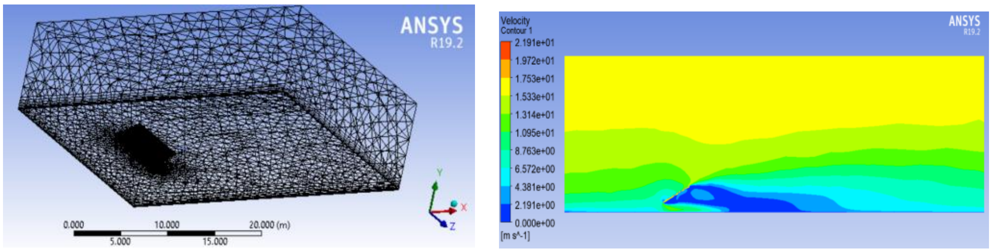


Figure 4: *3D Wire-mesh model and velocity contour for the validation model.*

	Experimental Values	Numerical Values (CFD)	ERROR
Mesh Elements	-	46,59453	-
Drag Coefficient	0.54	0.497	9 %
Lift Coefficient	-1.15	-1.08	7 %

Table 1: *Drag, Lift Coefficients obtained in the Current Study*

The results obtained from the numerical simulation shows a good agreement with the experimental values with error of 7 to 9%. Hence the model is validated with the Jubayer's experimental investigation.

b. Tilt Angle Analysis

Inclination angle (angle of tilt) of the solar panel is varied 0, 12.5, 25, 37.5, 45, and 60 Degree respectively. Velocity contour and velocity vector are as follows:

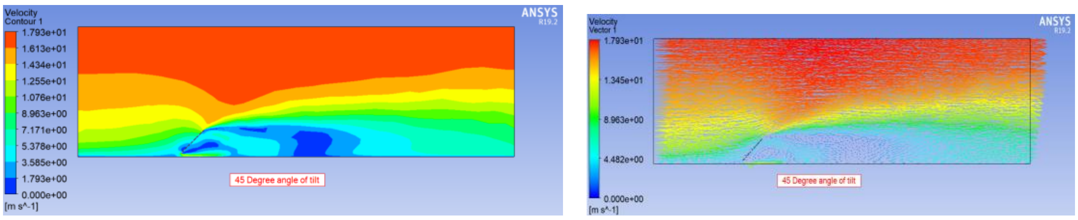


Figure 5: *Velocity contour(L) and velocity vector(R) for 45 Degree angle of tilt*

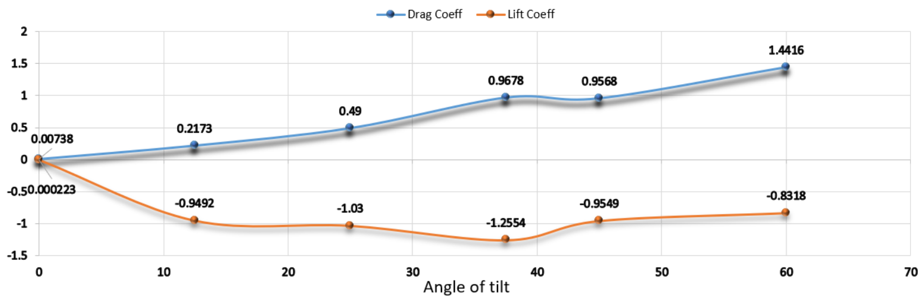


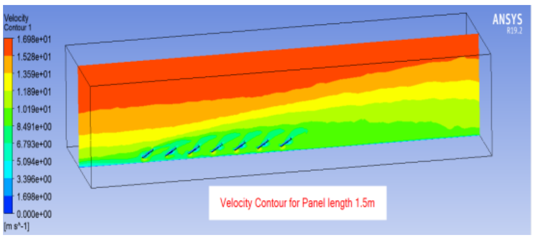
Figure 6: *Variation of drag and lift coefficient with the angle of tilt*

Drag coefficient (hence drag force) over solar panels increases as we increase the angle of tilt. So, angle of tilt of panel greater than 45 Degree is not recommended, in order to avoid higher drag force. We have considered solar panel inclination of 25 Degree for further study.

II)Investigation over array of ground mounted solar panel.

a. Effect of Panel Length Variation

Panel length of solar panel varied 1.5m, 2m and 2.5m respectively.



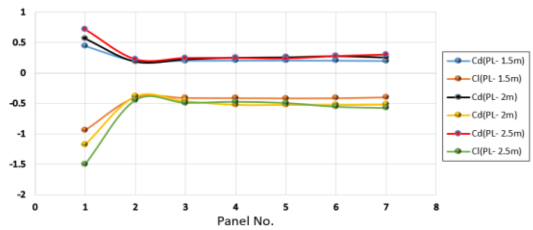


Figure 7: *Velocity contour for panel length 1.5m* **Figure 8:** *Panel length investigation study*

From the above plot, we can observe that with the increase in the panel length, there is a slight increase in the drag and lift coefficient. We have considered solar panel length of 1.6m(Standard Size) for further study.

b. Spacing Factor Analysis

For Spacing Gap study, Spacing factor of solar panels varied 2, 3, 4 and 5 respectively.

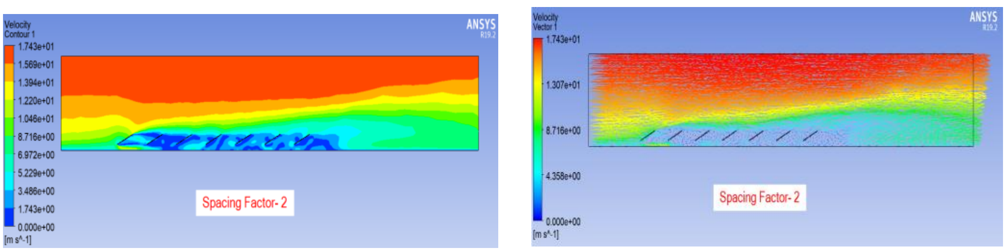


Figure 9: *Velocity contour and velocity vector for spacing factor 2.*

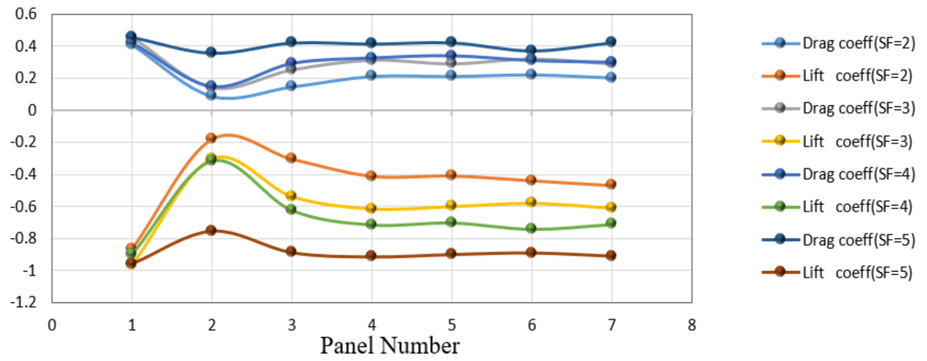


Figure 10: *Comparison of lift and drag coefficient for spacing factor 2.*

Sheltering effect is dominant when spacing gap between solar panels is less. With the increase in spacing gap the drag and lift force increase in the consecutive panels. So, Spacing gap should be lesser by taking into consideration that the shadow of previous panel should not fall on the consecutive solar panel. We have considered spacing factor 2 for further study.

c. <u>Effect of Clearance height of solar panel from the ground</u>

Clearance height from the ground is varied 0.6m, 0.8m, 1m, and respective drag and lift coefficient(forces) are studied as shown in the figure.

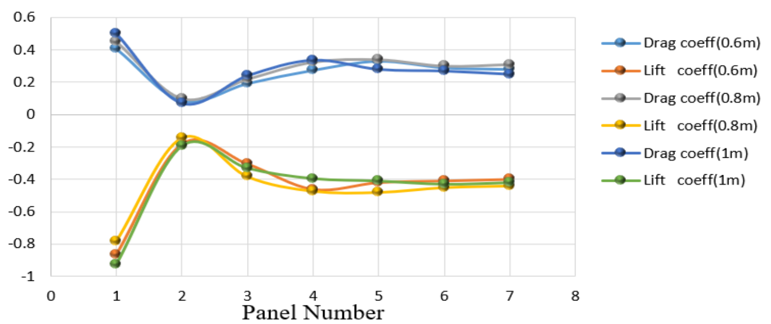


Figure 11: *Effect of Clearance height from the ground*

There is minor(negligible) effect of clearance height from the ground on the drag and lift coefficient over the solar panel. We have considered clearance height of 0.6m for further study.

d. <u>High order velocity investigation</u>

Wind Velocity is varied from 100kmph to 250kmph with 50kmph interval, and respective forces (lift and drag) are studied as shown in the figure.

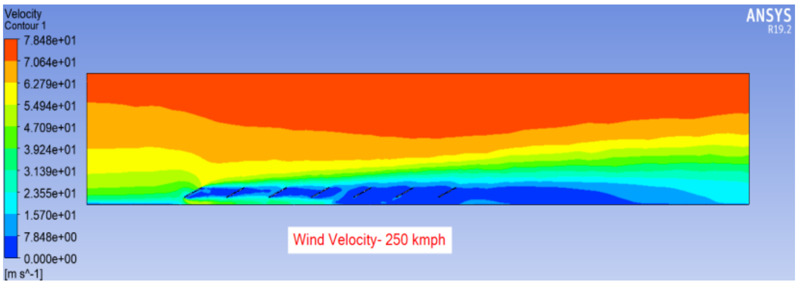


Figure 13: *Velocity contour for wind velocity 250kmph*

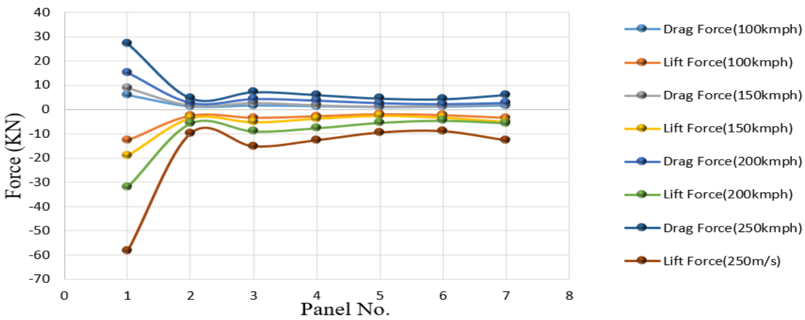


Figure 14: *Effect of variation of velocity*

When Wind velocity increased from 100Kmph to 250Kmph it is seen that drag force and lift force increases on respective panels(fig). The coefficient values of 5th panel can be taken as the asymptotically converged ones for the bulk of the panels that would be placed in solar farms. There is sudden drop of drag and lift force at the second row of solar panel due to wake effect.

Part B) Numerical investigation of solar panels mounted on inclined surface.

i)Terrain Inclination Study

Here, for inclined terrain we have considered three different slopes viz 15Degree, 30Degree and 45Degree respectively.

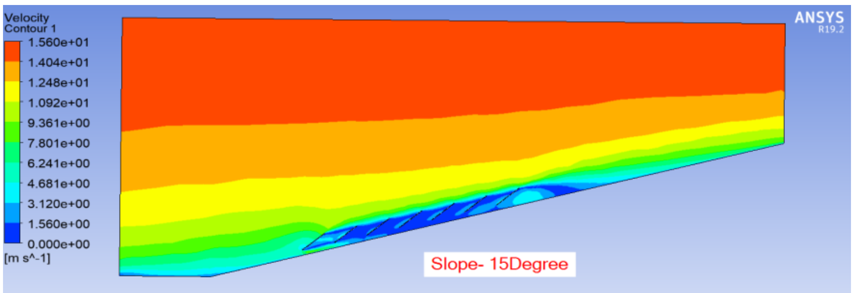


Figure 15: *Velocity Contour for the 15Degree slope of terrain.*

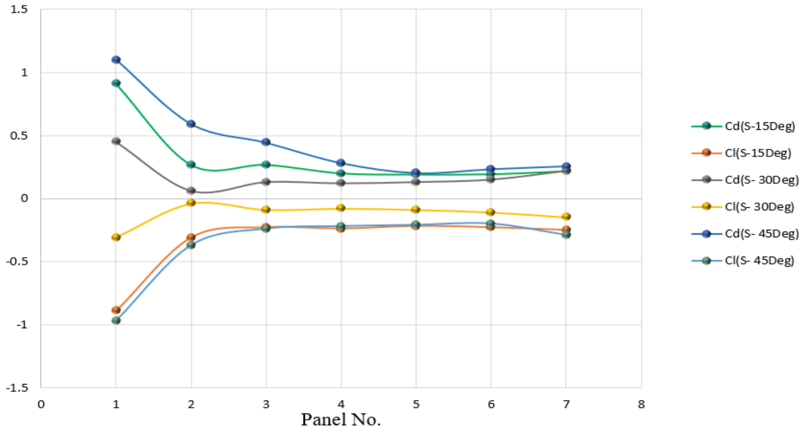


Figure 16: *Terrain Inclination Study*

From the graph it is seen that, drag and lift coefficient are minimum for 30Degree slope of the terrain and maximum for 45Degree terrain.

II) <u>Geographical topology-based investigation</u>

Three profiles of hills are considered in the study with constant height of 100m and length of the hill varied such that Height/Length ratio is 0.75, 1 and 1.25 respectively.

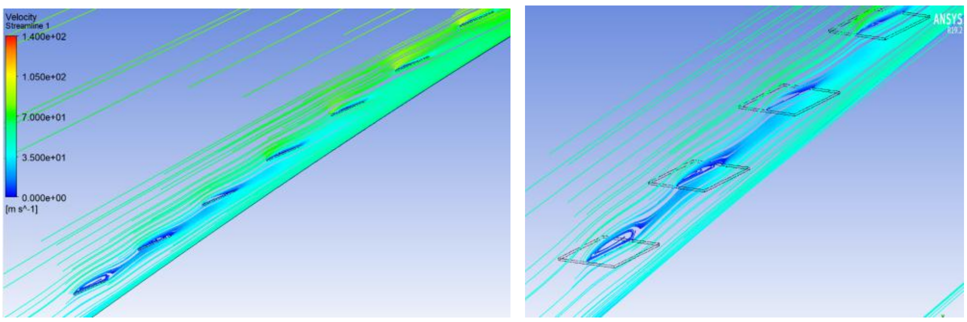


Figure 17: *Velocity streamlines at mid plan for hill profile with H/L ratio 1*

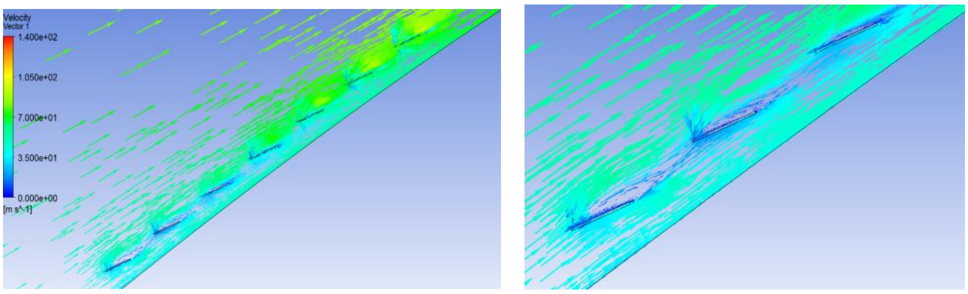


Figure 18: *Velocity vector at mid plan for hill profile with H/L ratio 1*

The drag force as well as lift force is maximum at the very first solar panel, and it reduces drastically for the second solar panel due to the wake effect (vortices formation near the surface of panel). From the graph we can see that variation of drag force and lift force with the different hill profiles (For H/L ratio of 0.5, 0.75 and 1 respectively).

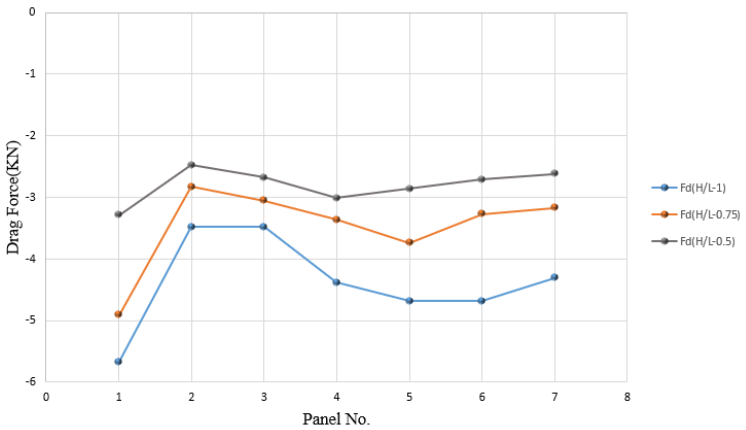


Figure 19: *Variation of drag force with different hill profiles*

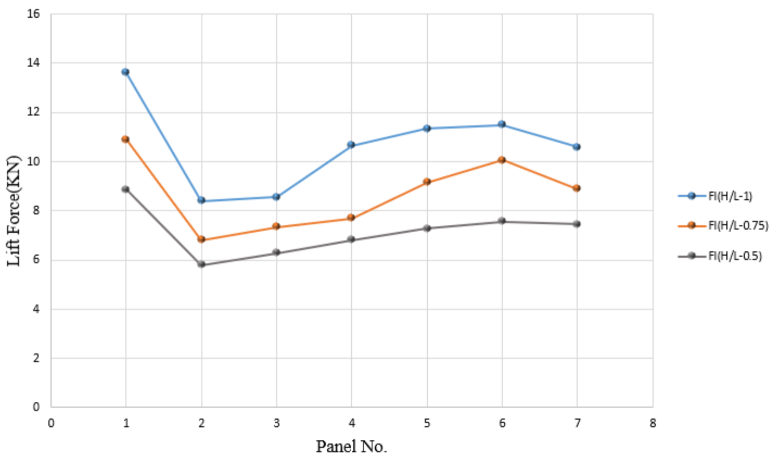


Figure 20: *Variation of lift force with different hill profiles*

Here, for the stiff hill with H/L=1, both drag and lift coefficient are maximum comparatively, and it is minimum for the hill with H/L=0.5. Hence, implementation of solar panels on the stiff hills is not recommended.

VI. CONCLUSION

From the current numerical analysis, it is observed that as we increase the H/L ratio from 0.5 to 1, the wind loads for the corresponding cases is increasing i.e. for stiff hills we get higher drag and lift forces. Also it is seen that the drag and lift force is highest on the first row of solar panel array, and it decreases significantly over the second row of array because of the wake effect (formation of vortices) after third row increases slightly and then after fifth row onwards it become almost constant.

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